AN INTRODUCTION TO ASTRONOMY



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1: An Introduction to Astronomy

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Licensing

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CHAPTER OVERVIEW

1: Science and the Universe - A Brief Tour

Such discoveries are what make astronomy such an exciting field for scientists and many others—but you will explore much more than just the objects in our universe and the latest discoveries about them. We will pay equal attention to the *process* by which we have come to understand the realms beyond Earth and the tools we use to increase that understanding. We gather information about the cosmos from the messages the universe sends our way. Because the stars are the fundamental building blocks of the universe, decoding the message of starlight has been a central challenge and triumph of modern astronomy. By the time you have finished reading this text, you will know a bit about how to read that message and how to understand what it is telling us.

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1.1: Introduction



Figure 1.1 : Distant Galaxies. These two interacting islands of stars (galaxies) are so far away that their light takes hundreds of millions of years to reach us on Earth (photographed with the Hubble Space Telescope). (credit: modification of work by NASA, ESA, the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration, and K. Noll (STScI))

We invite you to come along on a series of voyages to explore the universe as astronomers understand it today. Beyond Earth are vast and magnificent realms full of objects that have no counterpart on our home planet. Nevertheless, we hope to show you that the evolution of the universe has been directly responsible for your presence on Earth today.

Along your journey, you will encounter:

- a canyon system so large that, on Earth, it would stretch from Los Angeles to Washington, DC (Figure 1.2).

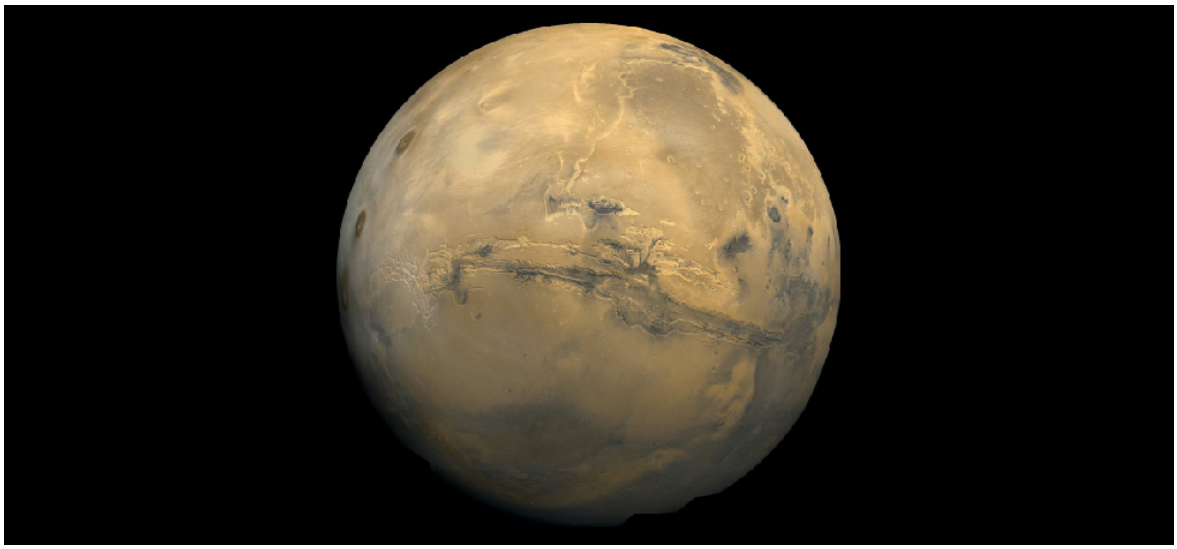


Figure 1.2 : Mars Mosaic. This image of Mars is centered on the Valles Marineris (Mariner Valley) complex of canyons, which is as long as the United States is wide. (credit: modification of work by NASA)

- a crater and other evidence on Earth that tell us that the dinosaurs (and many other creatures) died because of a cosmic collision.
- a tiny moon whose gravity is so weak that one good throw from its surface could put a baseball into orbit.
- a collapsed star so dense that to duplicate its interior we would have to squeeze every human being on Earth into a single raindrop.
- exploding stars whose violent end could wipe clean all of the life-forms on a planet orbiting a neighboring star (Figure 1.3).

- a “cannibal galaxy” that has already consumed a number of its smaller galaxy neighbors and is not yet finished finding new victims.
- a radio echo that is the faint but unmistakable signal of the creation event for our universe.

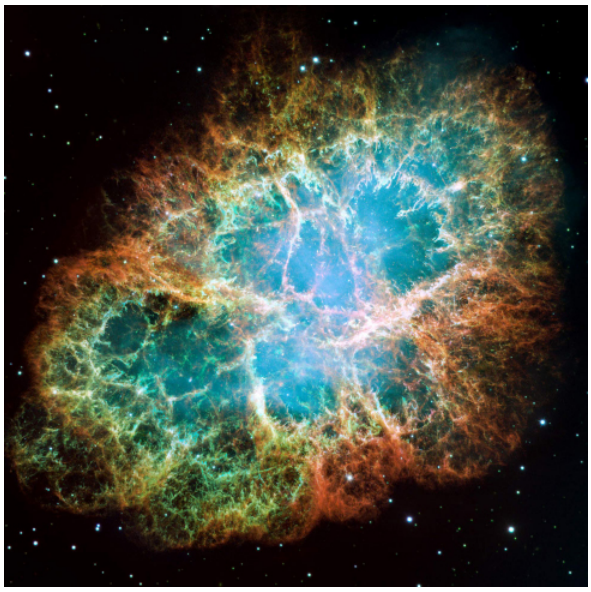


Figure 1.3 : Stellar Corpse. We observe the remains of a star that was seen to explode in our skies in 1054 (and was, briefly, bright enough to be visible during the daytime). Today, the remnant is called the Crab Nebula and its central region is seen here. Such exploding stars are crucial to the development of life in the universe. (credit: NASA, ESA, J. Hester (Arizona State University))

Such discoveries are what make astronomy such an exciting field for scientists and many others—but you will explore much more than just the objects in our universe and the latest discoveries about them. We will pay equal attention to the *process* by which we have come to understand the realms beyond Earth and the tools we use to increase that understanding.

We gather information about the cosmos from the messages the universe sends our way. Because the stars are the fundamental building blocks of the universe, decoding the message of starlight has been a central challenge and triumph of modern astronomy. By the time you have finished reading this text, you will know a bit about how to read that message and how to understand what it is telling us.

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1.2: The Nature of Astronomy

Astronomy is defined as the study of the objects that lie beyond our planet Earth and the processes by which these objects interact with one another. We will see, though, that it is much more. It is also humanity's attempt to organize what we learn into a clear history of the universe, from the instant of its birth in the Big Bang to the present moment. Throughout this book, we emphasize that science is a *progress report*—one that changes constantly as new techniques and instruments allow us to probe the universe more deeply.

In considering the history of the universe, we will see again and again that the cosmos *evolves*; it changes in profound ways over long periods of time. For example, the universe made the carbon, the calcium, and the oxygen necessary to construct something as interesting and complicated as you. Today, many billions of years later, the universe has evolved into a more hospitable place for life. Tracing the evolutionary processes that continue to shape the universe is one of the most important (and satisfying) parts of modern astronomy.

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1.3: The Nature of Science

The ultimate judge in science is always what nature itself reveals based on observations, experiments, models, and testing. Science is not merely a body of knowledge, but a *method* by which we attempt to understand nature and how it behaves. This method begins with many observations over a period of time. From the trends found through observations, scientists can *model* the particular phenomena we want to understand. Such models are always approximations of nature, subject to further testing.

As a concrete astronomical example, ancient astronomers constructed a model (partly from observations and partly from philosophical beliefs) that Earth was the center of the universe and everything moved around it in circular orbits. At first, our available observations of the Sun, Moon, and planets did fit this model; however, after further observations, the model had to be updated by adding circle after circle to represent the movements of the planets around Earth at the center. As the centuries passed and improved instruments were developed for keeping track of objects in the sky, the old model (even with a huge number of circles) could no longer explain all the observed facts. As we will see in the chapter on Observing the Sky: The Birth of Astronomy, a new model, with the Sun at the center, fit the experimental evidence better. After a period of philosophical struggle, it became accepted as our view of the universe.

When they are first proposed, new models or ideas are sometimes called *hypotheses*. You may think there can be no new hypotheses in a science such as astronomy—that everything important has already been learned. Nothing could be further from the truth. Throughout this textbook you will find discussions of recent, and occasionally still controversial, hypotheses in astronomy. For example, the significance that the huge chunks of rock and ice that hit Earth have for life on Earth itself is still debated. And while the evidence is strong that vast quantities of invisible “dark energy” make up the bulk of the universe, scientists have no convincing explanation for what the dark energy actually is. Resolving these issues will require difficult observations done at the forefront of our technology, and all such hypotheses need further testing before we incorporate them fully into our standard astronomical models.

This last point is crucial: a hypothesis must be a proposed explanation that can be *tested*. The most straightforward approach to such testing in science is to perform an experiment. If the experiment is conducted properly, its results either will agree with the predictions of the hypothesis or they will contradict it. If the experimental result is truly inconsistent with the hypothesis, a scientist must discard the hypothesis and try to develop an alternative. If the experimental result agrees with predictions, this does not necessarily prove that the hypothesis is absolutely correct; perhaps later experiments will contradict crucial parts of the hypothesis. But, the more experiments that agree with the hypothesis, the more likely we are to accept the hypothesis as a useful description of nature.

One way to think about this is to consider a scientist who was born and lives on an island where only black sheep live. Day after day the scientist encounters black sheep only, so he or she hypothesizes that all sheep are black. Although every observed sheep adds confidence to the hypothesis, the scientist only has to visit the mainland and observe one white sheep to prove the hypothesis wrong.

When you read about experiments, you probably have a mental picture of a scientist in a laboratory conducting tests or taking careful measurements. This is certainly the case for a biologist or a chemist, but what can astronomers do when our laboratory is the universe? It’s impossible to put a group of stars into a test tube or to order another comet from a scientific supply company.

As a result, astronomy is sometimes called an *observational* science; we often make our tests by observing many samples of the kind of object we want to study and noting carefully how different samples vary. New instruments and technology can let us look at astronomical objects from new perspectives and in greater detail. Our hypotheses are then judged in the light of this new information, and they pass or fail in the same way we would evaluate the result of a laboratory experiment.

Much of astronomy is also a *historical* science—meaning that what we observe has already happened in the universe and we can do nothing to change it. In the same way, a geologist cannot alter what has happened to our planet, and a paleontologist cannot bring an ancient animal back to life. While this can make astronomy challenging, it also gives us fascinating opportunities to discover the secrets of our cosmic past.

You might compare an astronomer to a detective trying to solve a crime that occurred before the detective arrived at the scene. There is lots of evidence, but both the detective and the scientist must sift through and organize the evidence to test various hypotheses about what actually happened. And there is another way in which the scientist is like a detective: they both must prove their case. The detective must convince the district attorney, the judge, and perhaps ultimately the jury that his hypothesis is correct. Similarly, the scientist must convince colleagues, editors of journals, and ultimately a broad cross-section of other scientists that her

hypothesis is provisionally correct. In both cases, one can only ask for evidence “beyond a reasonable doubt.” And sometimes new evidence will force both the detective and the scientist to revise their last hypothesis.

This self-correcting aspect of science sets it off from most human activities. Scientists spend a great deal of time questioning and challenging one another, which is why applications for project funding—as well as reports for publication in academic journals—go through an extensive process of *peer review*, which is a careful examination by other scientists in the same field. In science (after formal education and training), everyone is encouraged to improve upon experiments and to challenge any and all hypotheses. New scientists know that one of the best ways to advance their careers is to find a weakness in our current understanding of something and to correct it with a new or modified hypothesis.

This is one of the reasons science has made such dramatic progress. An undergraduate science major today knows more about science and math than did Sir Isaac Newton, one of the most renowned scientists who ever lived. Even in this introductory astronomy course, you will learn about objects and processes that no one a few generations ago even dreamed existed.

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1.4: The Laws of Nature

Over centuries scientists have extracted various *scientific laws* from countless observations, hypotheses, and experiments. These scientific laws are, in a sense, the “rules” of the game that nature plays. One remarkable discovery about nature—one that underlies everything you will read about in this text—is that the same laws apply everywhere in the universe. The rules that determine the motion of stars so far away that your eye cannot see them are the same laws that determine the arc of a baseball after a batter has hit it out of the park.

Note that without the existence of such universal laws, we could not make much headway in astronomy. If each pocket of the universe had different rules, we would have little chance of interpreting what happened in other “neighborhoods.” But, the consistency of the laws of nature gives us enormous power to understand distant objects without traveling to them and learning the local laws. In the same way, if every region of a country had completely different laws, it would be very difficult to carry out commerce or even to understand the behavior of people in those different regions. A consistent set of laws, though, allows us to apply what we learn or practice in one state to any other state.

This is not to say that our current scientific models and laws cannot change. New experiments and observations can lead to new, more sophisticated models—models that can include new phenomena and laws about their behavior. The general theory of relativity proposed by Albert Einstein is a perfect example of such a transformation that took place about a century ago; it led us to predict, and eventually to observe, a strange new class of objects that astronomers call *black holes*. Only the patient process of observing nature ever more carefully and precisely can demonstrate the validity of such new scientific models.

One important problem in describing scientific models has to do with the limitations of language. When we try to describe complex phenomena in everyday terms, the words themselves may not be adequate to do the job. For example, you may have heard the structure of the atom likened to a miniature solar system. While some aspects of our modern model of the atom do remind us of planetary orbits, many other of its aspects are fundamentally different.

This problem is the reason scientists often prefer to describe their models using equations rather than words. In this book, which is designed to introduce the field of astronomy, we use mainly words to discuss what scientists have learned. We avoid complex math, but if this course piques your interest and you go on in science, more and more of your studies will involve the precise language of mathematics.

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1.5: Numbers in Astronomy

In astronomy we deal with distances on a scale you may never have thought about before, with numbers larger than any you may have encountered. We adopt two approaches that make dealing with astronomical numbers a little bit easier. First, we use a system for writing large and small numbers called *scientific notation* (or sometimes *powers-of-ten notation*). This system is very appealing because it eliminates the many zeros that can seem overwhelming to the reader. In scientific notation, if you want to write a number such as 500,000,000, you express it as

Unexpected text node: 'Appendix C and Example 1.1 for more information. The second way we try to keep numbers simple is to use a consistent set of units—the metric International System of Units, or SI (from the French '

Système International d'Unités). The metric system is summarized in Appendix D (see Example 1.2).

Link to Learning

Watch this brief PBS animation that explains how scientific notation works and why it's useful.

A common unit astronomers use to describe distances in the universe is a light-year, which is the distance light travels during one year. Because light always travels at the same speed, and because its speed turns out to be the fastest possible speed in the universe, it makes a good standard for keeping track of distances. You might be confused because a "light-year" seems to imply that we are measuring time, but this mix-up of time and distance is common in everyday life as well. For example, when your friend asks where the movie theater is located, you might say "about 20 minutes from downtown."

So, how many kilometers are there in a light-year? Light travels at the amazing pace of

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Figure 1.4 : Orion Nebula. This beautiful cloud of cosmic raw material (gas and dust from which new stars and planets are being made) called the Orion Nebula is about 1400 light-years away. That's a distance of roughly 1.34×10^{16} kilometers—a pretty big number. The gas and dust in this region are illuminated by the intense light from a few extremely energetic adolescent stars. (credit: NASA, ESA, M. Robberto (Space Telescope Science Institute/ESA) and the Hubble Space Telescope Orion Treasury Project Team)

Example 1.1

Scientific Notation

In 2015, the richest human being on our planet had a net worth of $79.2 billion. Some might say this is an astronomical sum of money. Express this amount in scientific notation.

Solution

$79.2 billion can be written $79,200,000,000. Expressed in scientific notation it becomes $\$7.92 \times 10^{10}$

Example 1.2

Getting Familiar with a Light-Year

How many kilometers are there in a light-year?

Solution

Light travels 3×10^5 km in 1 s. So, let's calculate how far it goes in a year:

- There are 60 $\left(6 \times 10^1\right)$ s in 1 min, and 6×10^1 min in 1 h.
- Multiply these together and you find that there are 3.6×10^3 s/h.
- Thus, light covers $3 \times 10^5 \ \mathrm{km/s} \times 3.6 \times 10^3 \ \mathrm{s/h} = 1.08 \times 10^9 \ \mathrm{km/h}$.
- There are 24 or 2.4×10^1 h in a day, and 365.25 $\left(3.65 \times 10^2\right)$ days in 1 y.
- The product of these two numbers is 8.77×10^3 h/y.

- Multiplying this by 1.08×10^9 km/h gives 9.46×10^{12} km/light-year.

That's almost 10,000,000,000,000 km that light covers in a year. To help you imagine how long this distance is, we'll mention that a string 1 light-year long could fit around the circumference of Earth 236 million times.

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1.6: Consequences of Light Travel Time

There is another reason the speed of light is such a natural unit of distance for astronomers. Information about the universe comes to us almost exclusively through various forms of light, and all such light travels at the speed of light—that is, 1 light-year every year. This sets a limit on how quickly we can learn about events in the universe. If a star is 100 light-years away, the light we see from it tonight left that star 100 years ago and is just now arriving in our neighborhood. The soonest we can learn about any changes in that star is 100 years after the fact. For a star 500 light-years away, the light we detect tonight left 500 years ago and is carrying 500-year-old news.

Because many of us are accustomed to instant news from the Internet, some might find this frustrating.

“You mean, when I see that star up there,” you ask, “I won’t know what’s actually happening there for another 500 years?”

But this isn’t the most helpful way to think about the situation. For astronomers, *now* is when the light reaches us here on Earth. There is no way for us to know anything about that star (or other object) until its light reaches us.

But what at first may seem a great frustration is actually a tremendous benefit in disguise. If astronomers really want to piece together what has happened in the universe since its beginning, they must find evidence about each epoch (or period of time) of the past. Where can we find evidence today about cosmic events that occurred billions of years ago?

The delay in the arrival of light provides an answer to this question. The farther out in space we look, the longer the light has taken to get here, and the longer ago it left its place of origin. By looking billions of light-years out into space, astronomers are actually seeing billions of years into the past. In this way, we can reconstruct the history of the cosmos and get a sense of how it has evolved over time.

This is one reason why astronomers strive to build telescopes that can collect more and more of the faint light in the universe. The more light we collect, the fainter the objects we can observe. On average, fainter objects are farther away and can, therefore, tell us about periods of time even deeper in the past. Instruments such as the Hubble Space Telescope (Figure 1.5) and the Very Large Telescope in Chile (which you will learn about in the chapter on Astronomical Instruments), are giving astronomers views of deep space and deep time better than any we have had before.



Figure 1.5 : Telescope in Orbit. The Hubble Space Telescope, shown here in orbit around Earth, is one of many astronomical instruments in space. (credit: modification of work by European Space Agency)

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1.7: A Tour of the Universe

We can now take a brief introductory tour of the universe as astronomers understand it today to get acquainted with the types of objects and distances you will encounter throughout the text. We begin at home with Earth, a nearly spherical planet about 13,000 kilometers in diameter (Figure 1.6). A space traveler entering our planetary system would easily distinguish Earth from the other planets in our solar system by the large amount of liquid water that covers some two thirds of its crust. If the traveler had equipment to receive radio or television signals, or came close enough to see the lights of our cities at night, she would soon find signs that this watery planet has sentient life.



Figure 1.6 : Humanity's Home Base. This image shows the Western hemisphere as viewed from space 35,400 kilometers (about 22,000 miles) above Earth. Data about the land surface from one satellite was combined with another satellite's data about the clouds to create the image. (credit: modification of work by R. Stockli, A. Nelson, F. Hasler, NASA/ GSFC/ NOAA/ USGS)

Our nearest astronomical neighbor is Earth's satellite, commonly called the *Moon*. Figure 1.7 shows Earth and the Moon drawn to scale on the same diagram. Notice how small we have to make these bodies to fit them on the page with the right scale. The Moon's distance from Earth is about 30 times Earth's diameter, or approximately 384,000 kilometers, and it takes about a month for the Moon to revolve around Earth. The Moon's diameter is 3476 kilometers, about one fourth the size of Earth.



Figure 1.7 : Earth and Moon, Drawn to Scale. This image shows Earth and the Moon shown to scale for both size and distance. (credit: modification of work by NASA)

Light (or radio waves) takes 1.3 seconds to travel between Earth and the Moon. If you've seen videos of the Apollo flights to the Moon, you may recall that there was a delay of about 3 seconds between the time Mission Control asked a question and the time the astronauts responded. This was not because the astronauts were thinking slowly, but rather because it took the radio waves almost 3 seconds to make the round trip.

Earth revolves around our star, the Sun, which is about 150 million kilometers away—approximately 400 times as far away from us as the Moon. We call the average Earth–Sun distance an *astronomical unit* (AU) because, in the early days of astronomy, it was the most important measuring standard. Light takes slightly more than 8 minutes to travel 1 astronomical unit, which means the latest news we receive from the Sun is always 8 minutes old. The diameter of the Sun is about 1.5 million kilometers; Earth could fit comfortably inside one of the minor eruptions that occurs on the surface of our star. If the Sun were reduced to the size of a basketball, Earth would be a small apple seed about 30 meters from the ball.

It takes Earth 1 year (3×10^7 seconds) to go around the Sun at our distance; to make it around, we must travel at approximately 110,000 kilometers per hour. (If you, like many students, still prefer miles to kilometers, you might find the following trick helpful. To convert kilometers to miles, just multiply kilometers by 0.6. Thus, 110,000 kilometers per hour becomes 66,000 miles per hour.)

Because gravity holds us firmly to Earth and there is no resistance to Earth's motion in the vacuum of space, we participate in this extremely fast-moving trip without being aware of it day to day.

Earth is only one of eight planets that revolve around the Sun. These planets, along with their moons and swarms of smaller bodies such as dwarf planets, make up the solar system (Figure 1.8). A planet is defined as a body of significant size that orbits a star and does not produce its own light. (If a large body consistently produces its own light, it is then called a *star*.) Later in the book this definition will be modified a bit, but it is perfectly fine for now as you begin your voyage.

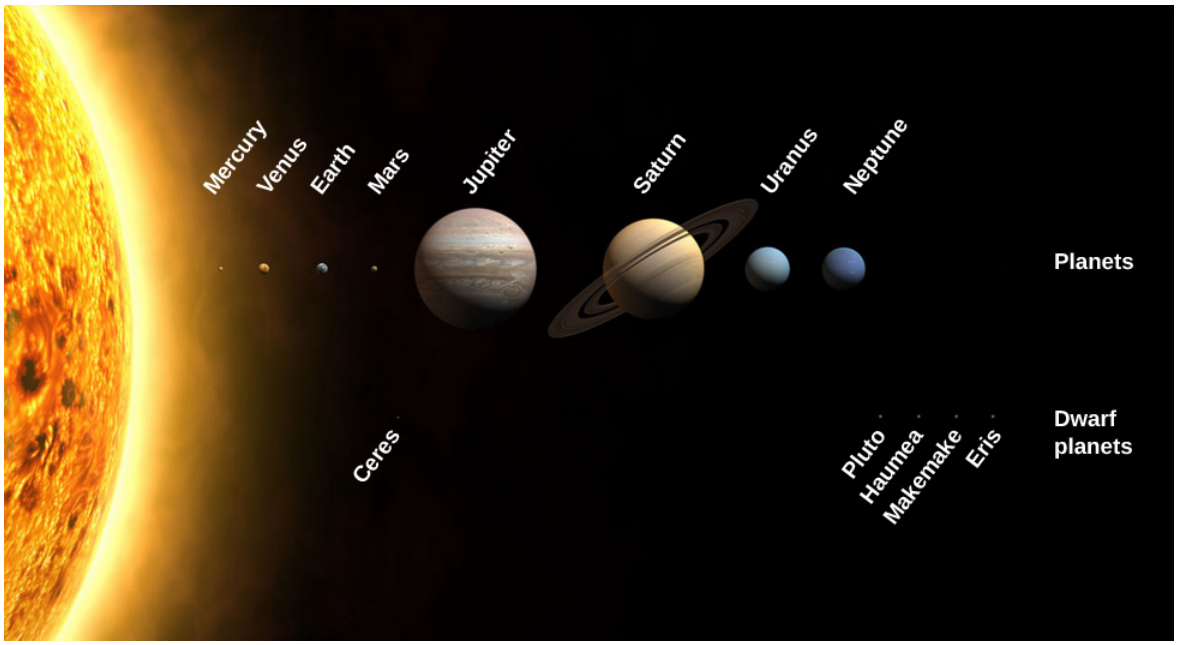


Figure 1.8 : Our Solar Family. The Sun, the planets, and some dwarf planets are shown with their sizes drawn to scale. The orbits of the planets are much more widely separated than shown in this drawing. Notice the size of Earth compared to the giant planets. (credit: modification of work by NASA)

We are able to see the nearby planets in our skies only because they reflect the light of our local star, the Sun. If the planets were much farther away, the tiny amount of light they reflect would usually not be visible to us. The planets we have so far discovered orbiting other stars were found from the pull their gravity exerts on their parent stars, or from the light they block from their stars when they pass in front of them. We can't see most of these planets directly, although a few are now being imaged directly.

The Sun is our local star, and all the other stars are also enormous balls of glowing gas that generate vast amounts of energy by nuclear reactions deep within. We will discuss the processes that cause stars to shine in more detail later in the book. The other stars look faint only because they are so very far away. If we continue our basketball analogy, Proxima Centauri, the nearest star beyond the Sun, which is 4.3 light-years away, would be almost 7000 kilometers from the basketball.

When you look up at a star-filled sky on a clear night, all the stars visible to the unaided eye are part of a single collection of stars we call the *Milky Way Galaxy*, or simply the *Galaxy*. (When referring to the Milky Way, we capitalize *Galaxy*; when talking about other galaxies of stars, we use lowercase *galaxy*.) The Sun is one of hundreds of billions of stars that make up the Galaxy; its extent, as we will see, staggers the human imagination. Within a sphere 10 light-years in radius centered on the Sun, we find roughly ten stars. Within a sphere 100 light-years in radius, there are roughly 10,000 (10^4) stars—far too many to count or name—but we have still traversed only a tiny part of the Milky Way Galaxy. Within a 1000-light-year sphere, we find some ten million (10^7) stars; within a sphere of 100,000 light-years, we finally encompass the entire Milky Way Galaxy.

Our Galaxy looks like a giant disk with a small ball in the middle. If we could move outside our Galaxy and look down on the disk of the Milky Way from above, it would probably resemble the galaxy in Figure 1.9, with its spiral structure outlined by the blue light of hot adolescent stars.



Figure 1.9 : Spiral Galaxy. This galaxy of billions of stars, called by its catalog number NGC 1073, is thought to be similar to our own Milky Way Galaxy. Here we see the giant wheel-shaped system with a bar of stars across its middle. (credit: NASA, ESA)

The Sun is somewhat less than 30,000 light-years from the center of the Galaxy, in a location with nothing much to distinguish it. From our position inside the Milky Way Galaxy, we cannot see through to its far rim (at least not with ordinary light) because the space between the stars is not completely empty. It contains a sparse distribution of gas (mostly the simplest element, hydrogen) intermixed with tiny solid particles that we call *interstellar dust*. This gas and dust collect into enormous clouds in many places in the Galaxy, becoming the raw material for future generations of stars. Figure 1.10 shows an image of the disk of the Galaxy as seen from our vantage point.



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Figure 1.10 : Milky Way Galaxy. Because we are inside the Milky Way Galaxy, we see its disk in cross-section flung across the sky like a great milky white avenue of stars with dark “rifts” of dust. In this dramatic image, part of it is seen above Trona Pinnacles in the California desert. (credit: Ian Norman)

Typically, the interstellar material is so extremely sparse that the space between stars is a much better vacuum than anything we can produce in terrestrial laboratories. Yet, the dust in space, building up over thousands of light-years, can block the light of more distant stars. Like the distant buildings that disappear from our view on a smoggy day in Los Angeles, the more distant regions of the Milky Way cannot be seen behind the layers of interstellar smog. Luckily, astronomers have found that stars and raw material shine with various forms of light, some of which do penetrate the smog, and so we have been able to develop a pretty good map of the Galaxy.

Recent observations, however, have also revealed a rather surprising and disturbing fact. There appears to be more—much more—to the Galaxy than meets the eye (or the telescope). From various investigations, we have evidence that much of our Galaxy is made of material we cannot currently observe directly with our instruments. We therefore call this component of the Galaxy *dark matter*. We know the dark matter is there by the pull its gravity exerts on the stars and raw material we can observe, but what this dark matter is made of and how much of it exists remain a mystery. Furthermore, this dark matter is not confined to our Galaxy; it appears to be an important part of other star groupings as well.

By the way, not all stars live by themselves, as the Sun does. Many are born in double or triple systems with two, three, or more stars revolving about each other. Because the stars influence each other in such close systems, multiple stars allow us to measure characteristics that we cannot discern from observing single stars. In a number of places, enough stars have formed together that we recognized them as star clusters (Figure 1.11). Some of the largest of the star clusters that astronomers have cataloged contain hundreds of thousands of stars and take up volumes of space hundreds of light-years across.



Figure 1.11 : Star Cluster. This large star cluster is known by its catalog number, M9. It contains some 250,000 stars and is seen more clearly from space using the Hubble Space Telescope. It is located roughly 25,000 light-years away. (credit: NASA, ESA)

You may hear stars referred to as “eternal,” but in fact no star can last forever. Since the “business” of stars is making energy, and energy production requires some sort of fuel to be used up, eventually all stars run out of fuel. This news should not cause you to panic, though, because our Sun still has at least 5 or 6 billion years to go. Ultimately, the Sun and all stars will die, and it is in their death throes that some of the most intriguing and important processes of the universe are revealed. For example, we now know that many of the atoms in our bodies were once inside stars. These stars exploded at the ends of their lives, recycling their material back into the reservoir of the Galaxy. In this sense, all of us are literally made of recycled “star dust.”

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1.8: The Universe on the Large Scale

In a very rough sense, you could think of the solar system as your house or apartment and the Galaxy as your town, made up of many houses and buildings. In the twentieth century, astronomers were able to show that, just as our world is made up of many, many towns, so the universe is made up of enormous numbers of galaxies. (We define the universe to be everything that exists that is accessible to our observations.) Galaxies stretch as far into space as our telescopes can see, many billions of them within the reach of modern instruments. When they were first discovered, some astronomers called galaxies *island universes*, and the term is aptly descriptive; galaxies do look like islands of stars in the vast, dark seas of intergalactic space.

The nearest galaxy, discovered in 1993, is a small one that lies 70,000 light-years from the Sun in the direction of the constellation Sagittarius, where the smog in our own Galaxy makes it especially difficult to discern. (A constellation, we should note, is one of the 88 sections into which astronomers divide the sky, each named after a prominent star pattern within it.) Beyond this Sagittarius dwarf galaxy lie two other small galaxies, about 160,000 light-years away. First recorded by Magellan's crew as he sailed around the world, these are called the *Magellanic Clouds* (Figure 1.12). All three of these small galaxies are satellites of the Milky Way Galaxy, interacting with it through the force of gravity. Ultimately, all three may even be swallowed by our much larger Galaxy, as other small galaxies have been over the course of cosmic time.



Figure 1.12 : Neighbor Galaxies. This image shows both the Large Magellanic Cloud and the Small Magellanic Cloud above the telescopes of the Atacama Large Millimeter/Submillimeter Array (ALMA) in the Atacama Desert of northern Chile. (credit: ESO, C. Malin)

The nearest large galaxy is a spiral quite similar to our own, located in the constellation of Andromeda, and is thus called the Andromeda galaxy; it is also known by one of its catalog numbers, M31 (Figure 1.13). M31 is a little more than 2 million light-years away and, along with the Milky Way, is part of a small cluster of more than 50 galaxies referred to as the *Local Group*.



Figure 1.13 : Closest Spiral Galaxy. The Andromeda galaxy (M31) is a spiral-shaped collection of stars similar to our own Milky Way. (credit: Adam Evans)

At distances of 10 to 15 million light-years, we find other small galaxy groups, and then at about 50 million light-years there are more impressive systems with thousands of member galaxies. We have discovered that galaxies occur mostly in clusters, both large and small (Figure 1.14).



Figure 1.14 : Fornax Cluster of Galaxies. In this image, you can see part of a cluster of galaxies located about 60 million light-years away in the constellation of Fornax. All the objects that are not pinpoints of light in the picture are galaxies of billions of stars. (credit: ESO, J. Emerson, VISTA. Acknowledgment: Cambridge Astronomical Survey Unit)

Some of the clusters themselves form into larger groups called *superclusters*. The Local Group is part of a supercluster of galaxies, called the Virgo Supercluster, which stretches over a diameter of 110 million light-years. We are just beginning to explore the structure of the universe at these enormous scales and are already encountering some unexpected findings.

At even greater distances, where many ordinary galaxies are too dim to see, we find *quasars*. These are brilliant centers of galaxies, glowing with the light of an extraordinarily energetic process. The enormous energy of the quasars is produced by gas that is heated to a temperature of millions of degrees as it falls toward a massive black hole and swirls around it. The brilliance of quasars makes them the most distant beacons we can see in the dark oceans of space. They allow us to probe the universe 10 billion light-years away or more, and thus 10 billion years or more in the past.

With quasars we can see way back close to the Big Bang explosion that marks the beginning of time. Beyond the quasars and the most distant visible galaxies, we have detected the feeble glow of the explosion itself, filling the universe and thus coming to us

from all directions in space. The discovery of this “afterglow of creation” is considered to be one of the most significant events in twentieth-century science, and we are still exploring the many things it has to tell us about the earliest times of the universe.

Measurements of the properties of galaxies and quasars in remote locations require large telescopes, sophisticated light-amplifying devices, and painstaking labor. Every clear night, at observatories around the world, astronomers and students are at work on such mysteries as the birth of new stars and the large-scale structure of the universe, fitting their results into the tapestry of our understanding.

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1.9: The Universe of the Very Small

The foregoing discussion has likely impressed on you that the universe is extraordinarily large and extraordinarily empty. On average, it is 10,000 times more empty than our Galaxy. Yet, as we have seen, even the Galaxy is mostly empty space. The air we breathe has about 10^{19} atoms in each cubic centimeter—and we usually think of air as empty space. In the interstellar gas of the Galaxy, there is about one atom in every cubic centimeter. Intergalactic space is filled so sparsely that to find one atom, on average, we must search through a cubic meter of space. Most of the universe is fantastically empty; places that are dense, such as the human body, are tremendously rare.

Even our most familiar solids are mostly space. If we could take apart such a solid, piece by piece, we would eventually reach the tiny molecules from which it is formed. Molecules are the smallest particles into which any matter can be divided while still retaining its chemical properties. A molecule of water (H_2O), for example, consists of two hydrogen atoms and one oxygen atom bonded together.

Molecules, in turn, are built of atoms, which are the smallest particles of an element that can still be identified as that element. For example, an atom of gold is the smallest possible piece of gold. Nearly 100 different kinds of atoms (elements) exist in nature. Most of them are rare, and only a handful account for more than 99% of everything with which we come in contact. The most abundant elements in the cosmos today are listed in Table 1.1; think of this table as the "greatest hits" of the universe when it comes to elements. Note that the list includes the four elements most common in life on Earth—hydrogen, carbon, nitrogen, and oxygen.

Table 1.1: The Cosmically Abundant Elements

Element[1]	Symbol	Number of Atoms per Million Hydrogen Atoms
Hydrogen	H	1,000,000
Helium	He	80,000
Carbon	C	450
Nitrogen	N	92
Oxygen	O	740
Neon	Ne	130
Magnesium	Mg	40
Silicon	Si	37
Sulfur	S	19
Iron	Fe	32

All atoms consist of a central, positively charged nucleus surrounded by negatively charged electrons. The bulk of the matter in each atom is found in the nucleus, which consists of positive protons and electrically neutral neutrons all bound tightly together in a very small space. Each element is defined by the number of protons in its atoms. Thus, any atom with 6 protons in its nucleus is called *carbon*, any with 50 protons is called *tin*, and any with 70 protons is called *ytterbium*. (For a list of the elements, see Appendix K.)

The distance from an atomic nucleus to its electrons is typically 100,000 times the size of the nucleus itself. This is why we say that even solid matter is mostly space. The typical atom is far emptier than the solar system out to Neptune. (The distance from Earth to the Sun, for example, is only 100 times the size of the Sun.) This is one reason atoms are not like miniature solar systems.

Remarkably, physicists have discovered that everything that happens in the universe, from the smallest atomic nucleus to the largest superclusters of galaxies, can be explained through the action of only four forces: gravity, electromagnetism (which combines the actions of electricity and magnetism), and two forces that act at the nuclear level. The fact that there are four forces (and not a million, or just one) has puzzled physicists and astronomers for many years and has led to a quest for a unified picture of nature.

Link to Learning

To construct an atom, particle by particle, check out this guided animation for building an atom.

Footnotes

- 1This list of elements is arranged in order of the atomic number, which is the number of protons in each nucleus.

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1.10: A Conclusion and a Beginning

If you are new to astronomy, you have probably reached the end of our brief tour in this chapter with mixed emotions. On the one hand, you may be fascinated by some of the new ideas you've read about and you may be eager to learn more. On the other hand, you may be feeling a bit overwhelmed by the number of topics we have covered, and the number of new words and ideas we have introduced. Learning astronomy is a little like learning a new language: at first it seems there are so many new expressions that you'll never master them all, but with practice, you soon develop facility with them.

At this point you may also feel a bit small and insignificant, dwarfed by the cosmic scales of distance and time. But, there is another way to look at what you have learned from our first glimpses of the cosmos. Let us consider the history of the universe from the Big Bang to today and compress it, for easy reference, into a single year. (We have borrowed this idea from Carl Sagan's 1977 Pulitzer Prize-winning book, *The Dragons of Eden*.)

On this scale, the Big Bang happened at the first moment of January 1, and this moment, when you are reading this chapter would be the end of the very last second of December 31. When did other events in the development of the universe happen in this "cosmic year?" Our solar system formed around September 10, and the oldest rocks we can date on Earth go back to the third week in September (Figure 1.15).

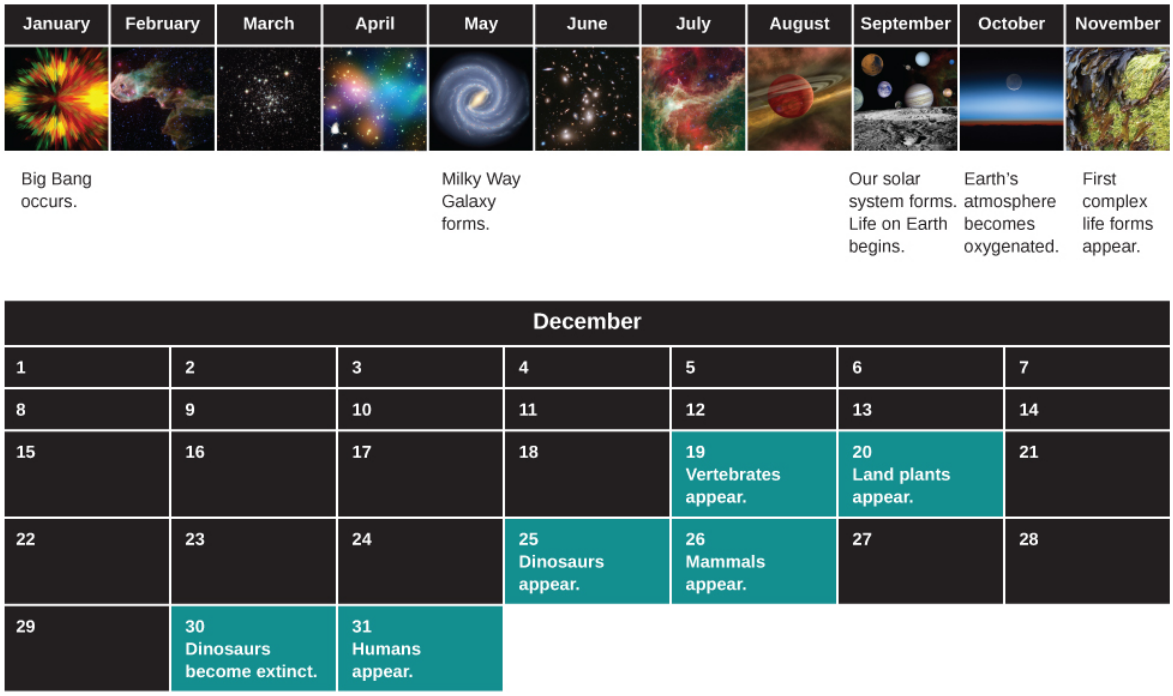


Figure 1.15 : Charting Cosmic Time. On a cosmic calendar, where the time since the Big Bang is compressed into 1 year, creatures we would call human do not emerge on the scene until the evening of December 31. (credit: February: modification of work by NASA, JPL-Caltech, W. Reach (SSC/Caltech); March: modification of work by ESA, Hubble and NASA, Acknowledgement: Giles Chapdelaine; April: modification of work by NASA, ESA, CFHT, CXO, M.J. Jee (University of California, Davis), A. Mahdavi (San Francisco State University); May: modification of work by NASA, JPL-Caltech; June: modification of work by NASA/ESA; July: modification of work by NASA, JPL-Caltech, Harvard-Smithsonian; August: modification of work by NASA, JPL-Caltech, R. Hurt (SSC-Caltech); September: modification of work by NASA; October: modification of work by NASA; November: modification of work by Dénes Emőke)

Where does the origin of human beings fall during the course of this cosmic year? The answer turns out to be the evening of December 31. The invention of the alphabet doesn't occur until the fiftieth second of 11:59 p.m. on December 31. And the beginnings of modern astronomy are a mere fraction of a second before the New Year. Seen in a cosmic context, the amount of time we have had to study the stars is minute, and our success in piecing together as much of the story as we have is remarkable.

Certainly our attempts to understand the universe are not complete. As new technologies and new ideas allow us to gather more and better data about the cosmos, our present picture of astronomy will very likely undergo many changes. Still, as you read our current progress report on the exploration of the universe, take a few minutes every once in a while just to savor how much you have already learned.

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1.11: For Further Exploration

Books

Miller, Ron, and William Hartmann. *The Grand Tour: A Traveler's Guide to the Solar System*. 3rd ed. Workman, 2005. This volume for beginners is a colorfully illustrated voyage among the planets.

Sagan, Carl. *Cosmos*. Ballantine, 2013 [1980]. This tome presents a classic overview of astronomy by an astronomer who had a true gift for explaining things clearly. (You can also check out Sagan's television series *Cosmos: A Personal Voyage* and Neil DeGrasse Tyson's current series *Cosmos: A Spacetime Odyssey.*)

Tyson, Neil DeGrasse, and Don Goldsmith. *Origins: Fourteen Billion Years of Cosmic Evolution.* Norton, 2004. This book provides a guided tour through the beginnings of the universe, galaxies, stars, planets, and life.

Websites

If you enjoyed the beautiful images in this chapter (and there are many more fabulous photos to come in other chapters), you may want to know where you can obtain and download such pictures for your own enjoyment. (Many astronomy images are from government-supported instruments or projects, paid for by tax dollars, and therefore are free of copyright laws.) Here are three resources we especially like:

- Astronomy Picture of the Day: apod.nasa.gov/apod/astropix.html. Two space scientists scour the Internet and select one beautiful astronomy image to feature each day. Their archives range widely, from images of planets and nebulae to rockets and space instruments; they also have many photos of the night sky. The search function (see the menu on the bottom of the page) works quite well for finding something specific among the many years' worth of daily images.
- Hubble Space Telescope Images: https://www.spacetelescope.org/images/. Here you can browse some of the remarkable images, select a particular subject in the menu boxes, or search for the name of an object that intrigues you in this book.
- National Aeronautics and Space Administration's (NASA's) Planetary Photojournal: photojournal.jpl.nasa.gov. This site features thousands of images from planetary exploration, with captions of varied length. You can select images by world, feature name, date, or catalog number, and download images in a number of popular formats. However, only NASA mission images are included. Note the Photojournal Search option on the menu at the top of the homepage to access ways to search their archives.

Videos

Powers of Ten: www.youtube.com/watch?v=0fKBhvDjuy0. This classic short video is a much earlier version of Powers of Ten, narrated by Philip Morrison (9:00).

The Known Universe: www.youtube.com/watch?v=17jymDn0W6U. This video tour from the American Museum of Natural History has realistic animation, music, and captions (6:30).

Wanderers: apod.nasa.gov/apod/ap141208.html. This video provides a tour of the solar system, with narrative by Carl Sagan, imagining other worlds with dramatically realistic paintings (3:50).

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CHAPTER OVERVIEW

2: Earth, Moon, and Sky

2.1: Thinking Ahead
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2.4: Keeping Time
2.5: The Calendar
2.6: Phases and Motions of the Moon
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2.1: Thinking Ahead



Figure 4.1 : Southern Summer. As captured with a fish-eye lens aboard the Atlantis Space Shuttle on December 9, 1993, Earth hangs above the Hubble Space Telescope as it is repaired. The reddish continent is Australia, its size and shape distorted by the special lens. Because the seasons in the Southern Hemisphere are opposite those in the Northern Hemisphere, it is summer in Australia on this December day. (credit: modification of work by NASA)

If Earth's orbit is nearly a perfect circle (as we saw in earlier chapters), why is it hotter in summer and colder in winter in many places around the globe? And why are the seasons in Australia or Peru the opposite of those in the United States or Europe?

The story is told that Galileo, as he left the Hall of the Inquisition following his retraction of the doctrine that Earth rotates and revolves about the Sun, said under his breath, "But nevertheless it moves." Historians are not sure whether the story is true, but certainly Galileo knew that Earth was in motion, whatever church authorities said.

It is the motions of Earth that produce the seasons and give us our measures of time and date. The Moon's motions around us provide the concept of the month and the cycle of lunar phases. In this chapter we examine some of the basic phenomena of our everyday world in their astronomical context.

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2.2: Earth and Sky

Learning Objectives

By the end of this section, you will be able to:

- Describe how latitude and longitude are used to map Earth
- Explain how right ascension and declination are used to map the sky

In order to create an accurate map, a mapmaker needs a way to uniquely and simply identify the location of all the major features on the map, such as cities or natural landmarks. Similarly, astronomical mapmakers need a way to uniquely and simply identify the location of stars, galaxies, and other celestial objects. On Earth maps, we divide the surface of Earth into a grid, and each location on that grid can easily be found using its *latitude* and *longitude* coordinate. Astronomers have a similar system for objects on the sky. Learning about these can help us understand the apparent motion of objects in the sky from various places on Earth.

Locating Places on Earth

Let's begin by fixing our position on the surface of planet Earth. As we discussed in Observing the Sky: The Birth of Astronomy, Earth's axis of rotation defines the locations of its North and South Poles and of its equator, halfway between. Two other directions are also defined by Earth's motions: east is the direction toward which Earth rotates, and west is its opposite. At almost any point on Earth, the four directions—north, south, east, and west—are well defined, despite the fact that our planet is round rather than flat. The only exceptions are exactly at the North and South Poles, where the directions east and west are ambiguous (because points exactly at the poles do not turn).

We can use these ideas to define a system of coordinates attached to our planet. Such a system, like the layout of streets and avenues in Manhattan or Salt Lake City, helps us find where we are or want to go. Coordinates on a sphere, however, are a little more complicated than those on a flat surface. We must define circles on the sphere that play the same role as the rectangular grid that you see on city maps.

A great circle is any circle on the surface of a sphere whose center is at the center of the sphere. For example, Earth's equator is a great circle on Earth's surface, halfway between the North and South Poles. We can also imagine a series of great circles that pass through both the North and South Poles. Each of the circles is called a meridian; they are each perpendicular to the equator, crossing it at right angles.

Any point on the surface of Earth will have a meridian passing through it (Figure 4.2). The meridian specifies the east-west location, or longitude, of the place. By international agreement (and it took many meetings for the world's countries to agree), longitude is defined as the number of degrees of arc along the equator between your meridian and the one passing through Greenwich, England, which has been designated as the Prime Meridian. The longitude of the Prime Meridian is defined as 0°.

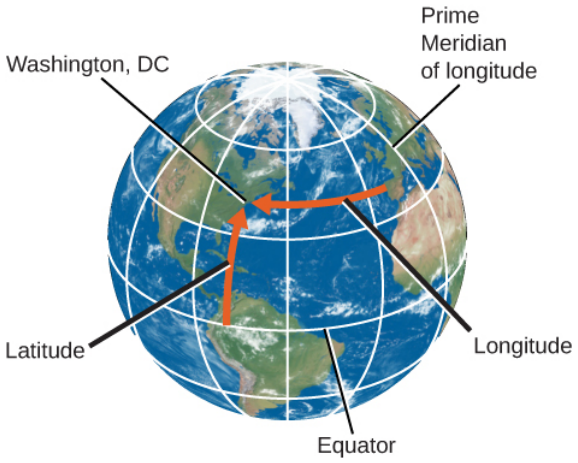


Figure 4.2 : Latitude and Longitude of Washington, DC. We use latitude and longitude to find cities like Washington, DC, on a globe. Latitude is the number of degrees north or south of the equator, and longitude is the number of degrees east or west of the Prime Meridian. Washington, DC's coordinates are 38° N and 77° W.

Why Greenwich, you might ask? Every country wanted 0° longitude to pass through its own capital. Greenwich, the site of the old Royal Observatory (Figure 4.3), was selected because it was between continental Europe and the United States, and because it was the site for much of the development of the method to measure longitude at sea. Longitudes are measured either to the east or to the west of the Greenwich meridian from 0° to 180°. As an example, the longitude of the clock-house benchmark of the U.S. Naval Observatory in Washington, DC, is 77.066° W.



Figure 4.3 : Royal Observatory in Greenwich, England. At the internationally agreed-upon zero point of longitude at the Royal Observatory Greenwich, tourists can stand and straddle the exact line where longitude "begins."(credit left: modification of work by "pdbreen"/Flickr; credit right: modification of work by Ben Sutherland)

Your latitude (or north-south location) is the number of degrees of arc you are away from the equator along your meridian. Latitudes are measured either north or south of the equator from 0° to 90°. (The latitude of the equator is 0°.) As an example, the latitude of the previously mentioned Naval Observatory benchmark is 38.921° N. The latitude of the South Pole is 90° S, and the latitude of the North Pole is 90° N.

Locating Places in the Sky

Positions in the sky are measured in a way that is very similar to the way we measure positions on the surface of Earth. Instead of latitude and longitude, however, astronomers use coordinates called declination and right ascension. To denote positions of objects in the sky, it is often convenient to make use of the fictitious celestial sphere. We saw in Observing the Sky: The Birth of Astronomy that the sky appears to rotate about points above the North and South Poles of Earth—points in the sky called the north celestial pole and the south celestial pole. Halfway between the celestial poles, and thus 90° from each pole, is the *celestial equator*, a great circle on the celestial sphere that is in the same plane as Earth's equator. We can use these markers in the sky to set up a system of celestial coordinates.

Declination on the celestial sphere is measured the same way that latitude is measured on the sphere of Earth: from the celestial equator toward the north (positive) or south (negative). So Polaris, the star near the north celestial pole, has a declination of almost +90°.

Right ascension (RA) is like longitude, except that instead of Greenwich, the arbitrarily chosen point where we start counting is the *vernal equinox*, a point in the sky where the *ecliptic* (the Sun's path) crosses the celestial equator. RA can be expressed either in units of angle (degrees) or in units of time. This is because the celestial sphere appears to turn around Earth once a day as our planet turns on its axis. Thus the 360° of RA that it takes to go once around the celestial sphere can just as well be set equal to 24 hours. Then each 15° of arc is equal to 1 hour of time. For example, the approximate celestial coordinates of the bright star Capella are RA $5h = 75^\circ$ and declination $+50^\circ$.

One way to visualize these circles in the sky is to imagine Earth as a transparent sphere with the terrestrial coordinates (latitude and longitude) painted on it with dark paint. Imagine the celestial sphere around us as a giant ball, painted white on the inside. Then imagine yourself at the center of Earth, with a bright light bulb in the middle, looking out through its transparent surface to the sky. The terrestrial poles, equator, and meridians will be projected as dark shadows on the celestial sphere, giving us the system of coordinates in the sky.

The Turning Earth

Why do many stars rise and set each night? Why, in other words, does the night sky seem to turn? We have seen that the apparent rotation of the celestial sphere could be accounted for either by a daily rotation of the sky around a stationary Earth or by the rotation of Earth itself. Since the seventeenth century, it has been generally accepted that it is Earth that turns, but not until the nineteenth century did the French physicist Jean Foucault provide an unambiguous demonstration of this rotation. In 1851, he suspended a 60-meter pendulum with a mass of about 25 kilograms from the dome of the Pantheon in Paris and started the pendulum swinging evenly. If Earth had not been turning, there would have been no alteration of the pendulum's plane of oscillation, and so it would have continued tracing the same path. Yet after a few minutes Foucault could see that the pendulum's plane of motion was turning. Foucault explained that it was not the pendulum that was shifting, but rather Earth that was turning beneath it (Figure 4.4). You can now find such pendulums in many science centers and planetariums around the world.



Figure 4.4 : Foucault's Pendulum. As Earth turns, the plane of oscillation of the Foucault pendulum shifts gradually so that over the course of 12 hours, all the targets in the circle at the edge of the wooden platform are knocked over in sequence. (credit: Manuel M. Vicente)

Can you think of other pieces of evidence that indicate that it is Earth and not the sky that is turning? (See Collaborative Group Activity A at the end of this chapter.)

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2.3: The Seasons

Learning Objectives

By the end of this section, you will be able to:

- Describe how the tilt of Earth's axis causes the seasons
- Explain how seasonal differences on Earth vary with latitude

One of the fundamental facts of life at Earth's midlatitudes, where most of this book's readers live, is that there are significant variations in the heat we receive from the Sun during the course of the year. We thus divide the year into *seasons*, each with its different amount of sunlight. The difference between seasons gets more pronounced the farther north or south from the equator we travel, and the seasons in the Southern Hemisphere are the opposite of what we find on the northern half of Earth. With these observed facts in mind, let us ask what causes the seasons.

Many people have believed that the seasons were the result of the changing distance between Earth and the Sun. This sounds reasonable at first: it should be colder when Earth is farther from the Sun. But the facts don't bear out this hypothesis. Although Earth's orbit around the Sun is an ellipse, its distance from the Sun varies by only about 3%. That's not enough to cause significant variations in the Sun's heating. To make matters worse for people in North America who hold this hypothesis, Earth is actually closest to the Sun in January, when the Northern Hemisphere is in the middle of winter. And if distance were the governing factor, why would the two hemispheres have opposite seasons? As we shall show, the seasons are actually caused by the 23.5° tilt of Earth's axis.

The Seasons and Sunshine

Figure 4.5 shows Earth's annual path around the Sun, with Earth's axis tilted by 23.5°. Note that our axis continues to point the same direction in the sky throughout the year. As Earth travels around the Sun, in June the Northern Hemisphere "leans into" the Sun and is more directly illuminated. In December, the situation is reversed: the Southern Hemisphere leans into the Sun, and the Northern Hemisphere leans away. In September and March, Earth leans "sideways"—neither into the Sun nor away from it—so the two hemispheres are equally favored with sunshine.

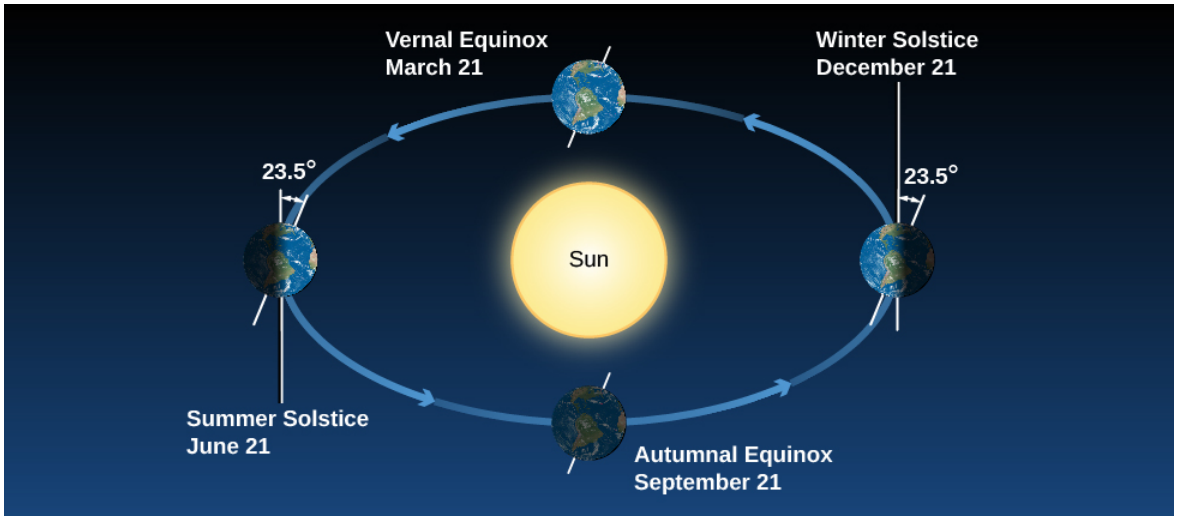


Figure 4.5 : Seasons. We see Earth at different seasons as it circles the Sun. In June, the Northern Hemisphere "leans into" the Sun, and those in the North experience summer and have longer days. In December, during winter in the Northern Hemisphere, the Southern Hemisphere "leans into" the Sun and is illuminated more directly. In spring and autumn, the two hemispheres receive more equal shares of sunlight.[1]

How does the Sun's favoring one hemisphere translate into making it warmer for us down on the surface of Earth? There are two effects we need to consider. When we lean into the Sun, sunlight hits us at a more direct angle and is more effective at heating Earth's surface (Figure 4.6). You can get a similar effect by shining a flashlight onto a wall. If you shine the flashlight straight on, you get an intense spot of light on the wall. But if you hold the flashlight at an angle (if the wall "leans out" of the beam), then the

spot of light is more spread out. Like the straight-on light, the sunlight in June is more direct and intense in the Northern Hemisphere, and hence more effective at heating.

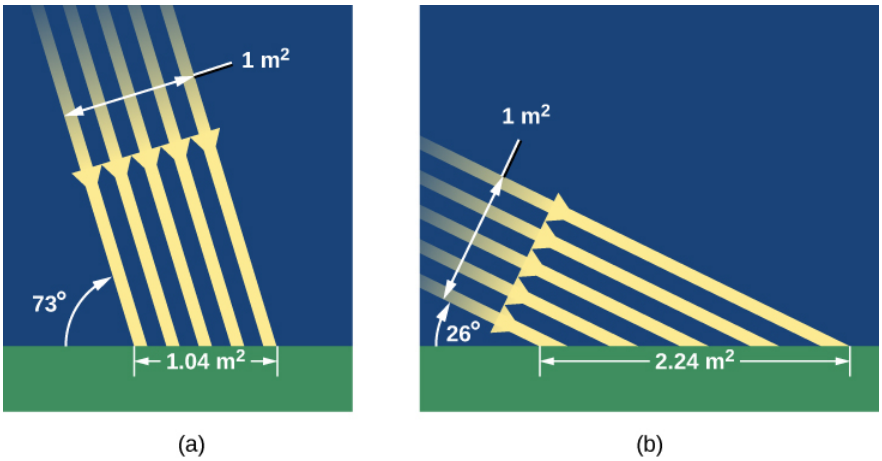


Figure 4.6 : The Sun's Rays in Summer and Winter. (a) In summer, the Sun appears high in the sky and its rays hit Earth more directly, spreading out less. (b) In winter, the Sun is low in the sky and its rays spread out over a much wider area, becoming less effective at heating the ground.

The second effect has to do with the length of time the Sun spends above the horizon (Figure 4.7). Even if you've never thought about astronomy before, we're sure you have observed that the hours of daylight increase in summer and decrease in winter. Let's see why this happens.

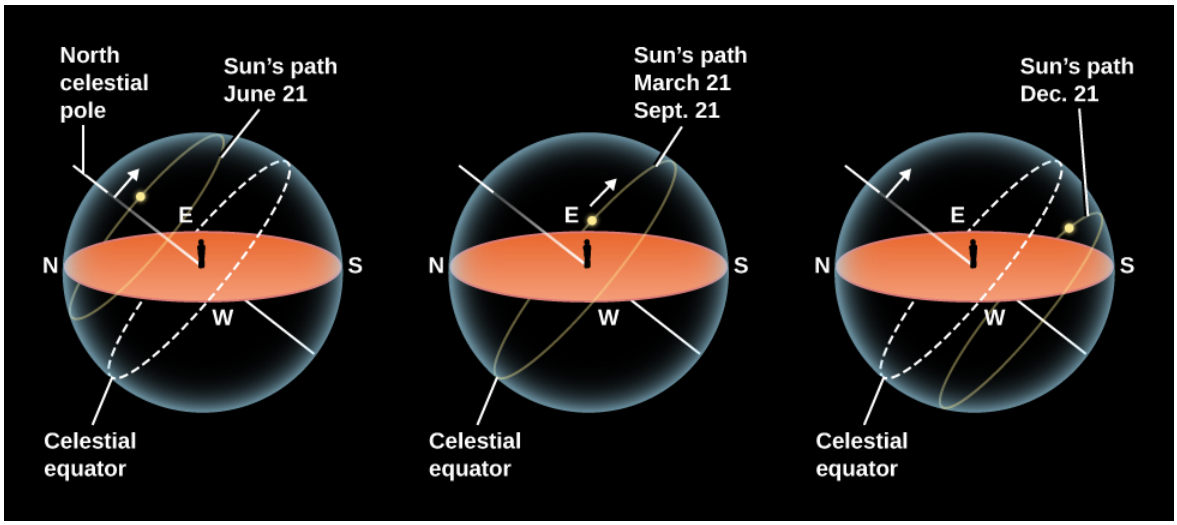


Figure 4.7 : The Sun's Path in the Sky for Different Seasons. On June 21, the Sun rises north of east and sets north of west. For observers in the Northern Hemisphere of Earth, the Sun spends about 15 hours above the horizon in the United States, meaning more hours of daylight. On December 21, the Sun rises south of east and sets south of west. It spends 9 hours above the horizon in the United States, which means fewer hours of daylight and more hours of night in northern lands (and a strong need for people to hold celebrations to cheer themselves up). On March 21 and September 21, the Sun spends equal amounts of time above and below the horizon in both hemispheres.

As we saw in Observing the Sky: The Birth of Astronomy, an equivalent way to look at our path around the Sun each year is to pretend that the Sun moves around Earth (on a circle called the ecliptic). Because Earth's axis is tilted, the ecliptic is tilted by about 23.5° relative to the celestial equator (review Figure 2.7). As a result, where we see the Sun in the sky changes as the year wears on.

In June, the Sun is north of the celestial equator and spends more time with those who live in the Northern Hemisphere. It rises high in the sky and is above the horizon in the United States for as long as 15 hours. Thus, the Sun not only heats us with more direct rays, but it also has more time to do it each day. (Notice in Figure 4.7 that the Northern Hemisphere's gain is the Southern Hemisphere's loss. There the June Sun is low in the sky, meaning fewer daylight hours. In Chile, for example, June is a colder, darker time of year.) In December, when the Sun is south of the celestial equator, the situation is reversed.

Link to Learning

The Motions of the Sun Simulator from Columbia University's Center for Teaching and Learning provides a demonstration of the Sun's apparent motion in the sky as the Earth rotates each day, and its changing altitude with latitude and time of year.

Let's look at what the Sun's illumination on Earth looks like at some specific dates of the year, when these effects are at their maximum. On or about June 21 (the date we who live in the Northern Hemisphere call the *summer solstice* or sometimes the first day of summer), the Sun shines down most directly upon the Northern Hemisphere of Earth. It appears about 23° north of the equator, and thus, on that date, it passes through the zenith of places on Earth that are at 23° N latitude. The situation is shown in detail in Figure 4.8. To a person at 23° N (near Hawaii, for example), the Sun is directly overhead at noon. This latitude, where the Sun can appear at the zenith at noon on the first day of summer, is called the *Tropic of Cancer*.

We also see in Figure 4.8 that the Sun's rays shine down all around the North Pole at the solstice. As Earth turns on its axis, the North Pole is continuously illuminated by the Sun; all places within 23° of the pole have sunshine for 24 hours. The Sun is as far north on this date as it can get; thus, 90° – 23° (or 67° N) is the southernmost latitude where the Sun can be seen for a full 24-hour period (sometimes called the "land of the midnight Sun"). That circle of latitude is called the *Arctic Circle*.

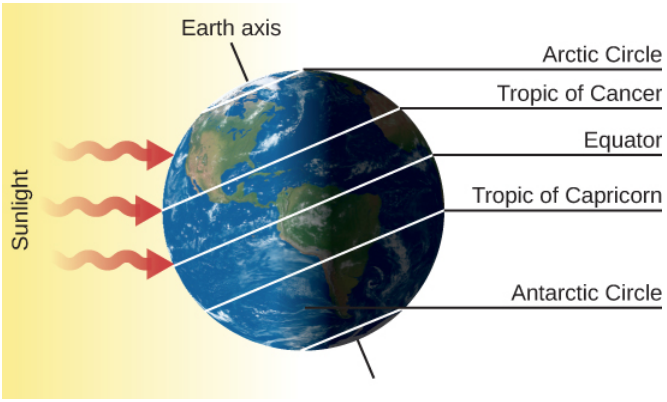


Figure 4.8 : Earth on June 21. This is the date of the summer solstice in the Northern Hemisphere. Note that as Earth turns on its axis (the line connecting the North and South Poles), the North Pole is in constant sunlight while the South Pole is veiled in 24 hours of darkness. The Sun is at the zenith for observers on the Tropic of Cancer.

Many early cultures scheduled special events around the summer solstice to celebrate the longest days and thank their gods for making the weather warm. This required people to keep track of the lengths of the days and the northward trek of the Sun in order to know the right day for the "party." (You can do the same thing by watching for several weeks, from the same observation point, where the Sun rises or sets relative to a fixed landmark. In spring, the Sun will rise farther and farther north of east, and set farther and farther north of west, reaching the maximum around the summer solstice.)

Now look at the South Pole in Figure 4.8. On June 21, all places within 23° of the South Pole—that is, south of what we call the *Antarctic Circle*—do not see the Sun at all for 24 hours.

The situation is reversed 6 months later, about December 21 (the date of the *winter solstice*, or the first day of winter in the Northern Hemisphere), as shown in Figure 4.9. Now it is the Arctic Circle that has the 24-hour night and the Antarctic Circle that has the midnight Sun. At latitude 23° S, called the *Tropic of Capricorn*, the Sun passes through the zenith at noon. Days are longer in the Southern Hemisphere and shorter in the north. In the United States and Southern Europe, there may be only 9 or 10 hours of sunshine during the day. It is winter in the Northern Hemisphere and summer in the Southern Hemisphere.

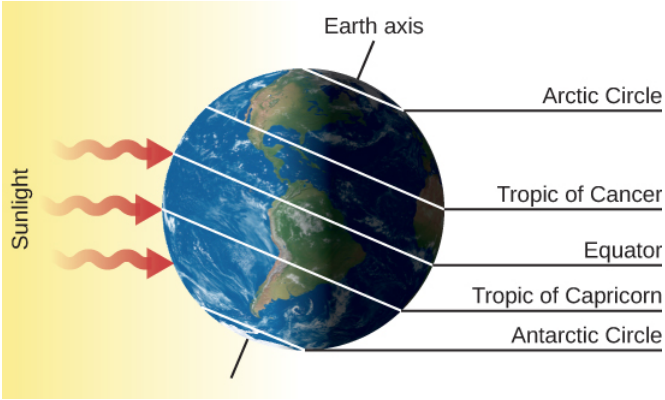


Figure 4.9 : Earth on December 21. This is the date of the winter solstice in the Northern Hemisphere. Now the North Pole is in darkness for 24 hours and the South Pole is illuminated. The Sun is at the zenith for observers on the Tropic of Capricorn and thus is low in the sky for the residents of the Northern Hemisphere.

Example 4.1: Seasonal Variations

As you can see in Figure 4.8, the Tropic of Cancer is the latitude for which the Sun is directly overhead on the summer solstice. At this time, the Sun is at a declination of 23° N of the celestial equator, and the corresponding latitude on Earth is 23° N of the equator. If Earth were tilted a bit less, then the Tropic of Cancer would be at a lower latitude, closer to the equator.

The Arctic Circle marks the southernmost latitude for which the day length is 24 hours on the day of the summer solstice. This is located at 90° – 23° = 67° N of Earth's equator. If Earth were tilted a bit less, then the Arctic Circle would move farther North. In the limit at which Earth is not tilted at all (its axis is perpendicular to the ecliptic), the Tropic of Cancer would be right on Earth's equator, and the Arctic Circle would simply be the North Pole. Suppose the tilt of Earth's axis were tilted only 5°. What would be the effect on the seasons and the locations of the Tropic of Cancer and Arctic Circle?

Solution

If Earth were tilted less, the seasons would be less extreme. The variation in day length and direct sunlight would be very small over the course of a year, and the Sun's daily path in the sky would not vary much. If Earth were tilted by 5°, the Sun's position on the day of the summer solstice would be 5° N of the celestial equator, so the Tropic of Cancer would be at the corresponding latitude on Earth of 5° N of the Equator. The Arctic Circle would be located at 90° – 5° = 85° N of the equator.

Exercise 2.3.1

Suppose the tilt of Earth's axis were 16°. What, then, would be the difference in latitude between the Arctic Circle and the Tropic of Cancer? What would be the effect on the seasons compared with that produced by the actual tilt of 23°?

Answer

The Tropic of Cancer is at a latitude equal to Earth's tilt, so in this case, it would be at 16° N latitude. The Arctic Circle is at a latitude equal to 90° minus Earth's tilt, or 90° – 16° = 74°. The difference between these two latitudes is 74° – 16° = 58°. Since the tilt of Earth is less, there would be less variation in the tilt of Earth and less variation in the Sun's paths throughout the year, so there would be milder seasonal changes.

Link to Learning

The Columbia University's Center for Teaching and Learning's Motions of the Sun Simulator allows you to see how the Sun's changing altitude over the course of the year changes the intensity of lighting experienced on Earth. Select the "Step by day" option before running the animation to illustrate this effect.

Many cultures that developed some distance north of the equator have a celebration around December 21 to help people deal with the depressing lack of sunlight and the often dangerously cold temperatures. Originally, this was often a time for huddling with family and friends, for sharing the reserves of food and drink, and for rituals asking the gods to return the light and heat and turn the cycle of the seasons around. Many cultures constructed elaborate devices for anticipating when the shortest day of the year was coming. Stonehenge in England, built long before the invention of writing, is probably one such device. In our own time, we continue the winter solstice tradition with various holiday celebrations around that December date.

Halfway between the solstices, on about March 21 and September 21, the Sun is on the celestial equator. From Earth, it appears above our planet's equator and favors neither hemisphere. Every place on Earth then receives roughly 12 hours of sunshine and 12 hours of night. The points where the Sun crosses the celestial equator are called the *vernal* (spring) and *autumnal* (fall) *equinoxes*.

The Seasons at Different Latitudes

The seasonal effects are different at different latitudes on Earth. Near the equator, for instance, all seasons are much the same. Every day of the year, the Sun is up half the time, so there are approximately 12 hours of sunshine and 12 hours of night. Local residents define the seasons by the amount of rain (wet season and dry season) rather than by the amount of sunlight. As we travel north or south, the seasons become more pronounced, until we reach extreme cases in the Arctic and Antarctic.

At the North Pole, all celestial objects that are north of the celestial equator are always above the horizon and, as Earth turns, circle around parallel to it. The Sun is north of the celestial equator from about March 21 to September 21, so at the North Pole, the Sun rises when it reaches the vernal equinox and sets when it reaches the autumnal equinox. Each year there are 6 months of sunshine at each pole, followed by 6 months of darkness.

Example 4.2: The Position of the Sun in the Sky

The Sun's coordinates on the celestial sphere range from a declination of 23° N of the celestial equator (or +23°) to a declination 23° S of the celestial equator (or –23°). So, the Sun's altitude at noon, when it crosses the meridian, varies by a total of 46°. What is the altitude of the Sun at noon on March 21, as seen from a place on Earth's equator? What is its altitude on June 21, as seen from a place on Earth's equator?

Solution

On Earth's equator, the celestial equator passes through the zenith. On March 21, the Sun is crossing the celestial equator, so it should be found at the zenith (90°) at noon. On June 21, the Sun is 23° N of the celestial equator, so it will be 23° away from the zenith at noon. The altitude above the horizon will be 23° less than the altitude of the zenith (90°), so it is 90° – 23° = 67° above the horizon.

Exercise 2.3.1

What is the altitude of the Sun at noon on December 21, as seen from a place on the Tropic of Cancer?

Answer

On the day of the winter solstice, the Sun is located about 23° S of the celestial equator. From the Tropic of Cancer, a latitude of 23° N, the zenith would be a declination of 23° N. The difference in declination between zenith and the position of the Sun is 46°, so the Sun would be 46° away from the zenith. That means it would be at an altitude of 90° – 46° = 44°.

Clarifications about the Real World

In our discussions so far, we have been describing the rising and setting of the Sun and stars as they would appear if Earth had little or no atmosphere. In reality, however, the atmosphere has the curious effect of allowing us to see a little way "over the horizon." This effect is a result of *refraction*, the bending of light passing through air or water, something we will discuss in Astronomical

Instruments. Because of this atmospheric refraction (and the fact that the Sun is not a point of light but a disk), the Sun appears to rise earlier and to set later than it would if no atmosphere were present.

In addition, the atmosphere scatters light and provides some twilight illumination even when the Sun is below the horizon. Astronomers define morning twilight as beginning when the Sun is 18° below the horizon, and evening twilight extends until the Sun sinks more than 18° below the horizon.

These atmospheric effects require small corrections in many of our statements about the seasons. At the equinoxes, for example, the Sun appears to be above the horizon for a few minutes longer than 12 hours, and below the horizon for fewer than 12 hours. These effects are most dramatic at Earth's poles, where the Sun actually can be seen more than a week before it reaches the celestial equator.

You probably know that the summer solstice (June 21) is not the warmest day of the year, even if it is the longest. The hottest months in the Northern Hemisphere are July and August. This is because our weather involves the air and water covering Earth's surface, and these large reservoirs do not heat up instantaneously. You have probably observed this effect for yourself; for example, a pond does not get warm the moment the Sun rises but is warmest late in the afternoon, after it has had time to absorb the Sun's heat. In the same way, Earth gets warmer after it has had a chance to absorb the extra sunlight that is the Sun's summer gift to us. And the coldest times of winter are a month or more after the winter solstice.

Footnotes

- 1Note that the dates indicated for the solstices and equinoxes are approximate; depending on the year, they may occur a day or two earlier or later.

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2.4: Keeping Time

Learning Objectives

By the end of this section, you will be able to:

- Explain the difference between the solar day and the sidereal day
- Explain mean solar time and the reason for time zones

The measurement of time is based on the rotation of Earth. Throughout most of human history, time has been reckoned by positions of the Sun and stars in the sky. Only recently have mechanical and electronic clocks taken over this function in regulating our lives.

The Length of the Day

The most fundamental astronomical unit of time is the day, measured in terms of the rotation of Earth. There is, however, more than one way to define the day. Usually, we think of it as the rotation period of Earth with respect to the Sun, called the solar day. After all, for most people sunrise is more important than the rising time of Arcturus or some other star, so we set our clocks to some version of Sun-time. However, astronomers also use a sidereal day, which is defined in terms of the rotation period of Earth with respect to the stars.

A solar day is slightly longer than a sidereal day because (as you can see from Figure 4.10) Earth not only turns but also moves along its path around the Sun in a day. Suppose we start when Earth's orbital position is at day 1, with both the Sun and some distant star (located in the direction indicated by the long white arrow pointing left), directly in line with the zenith for the observer on Earth. When Earth has completed one rotation with respect to the distant star and is at day 2, the long arrow again points to the same distant star. However, notice that because of the movement of Earth along its orbit from day 1 to 2, the Sun has not yet reached a position above the observer. To complete a solar day, Earth must rotate an additional amount, equal to 1/365 of a full turn. The time required for this extra rotation is 1/365 of a day, or about 4 minutes. So the solar day is about 4 minutes longer than the sidereal day.

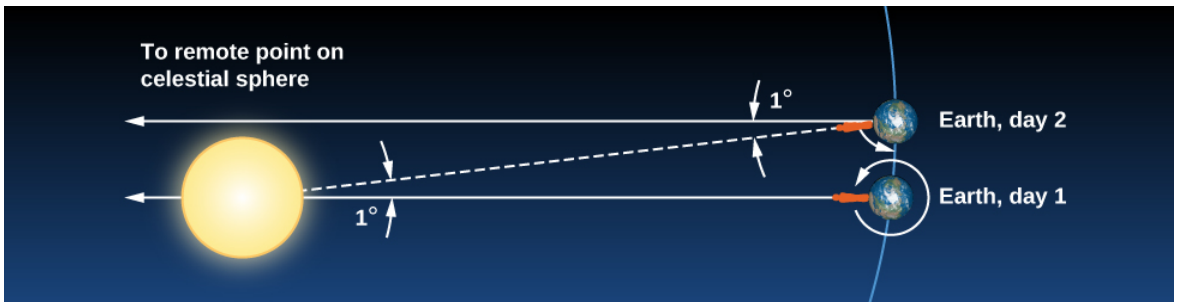


Figure 4.10 : Difference Between a Sidereal Day and a Solar Day. This is a top view, looking down as Earth orbits the Sun. Because Earth moves around the Sun (roughly 1° per day), after one complete rotation of Earth relative to the stars, we do not see the Sun in the same position.

Because our ordinary clocks are set to solar time, stars rise 4 minutes earlier each day. Astronomers prefer sidereal time for planning their observations because in that system, a star rises at the same time every day.

Example 4.3: Sidereal Time and Solar Time

The Sun makes a complete circle in the sky approximately every 24 hours, while the stars make a complete circle in the sky in 4 minutes less time, or 23 hours and 56 minutes. This causes the positions of the stars at a given time of day or night to change slightly each day. Since stars rise 4 minutes earlier each day, that works out to about 2 hours per month $(4\text{minutes} \times 30 = 120\text{minutes or} 2\text{hours})$. So, if a particular constellation rises at sunset during the winter, you can be sure that by the summer, it will rise about 12 hours earlier, with the sunrise, and it will not be so easily visible in the night sky. Let's say that tonight the bright star Sirius rises at 7:00 p.m. from a given location so that by midnight, it is very high in the sky. At what time will Sirius rise in three months?

Solution

In three months' time, Sirius will be rising earlier by:

$$90 \text{ days} \times \frac{4 \text{ minutes}}{\text{day}} = 360 \text{ minutes or } 6$$

It will rise at about 1:00 p.m. and be high in the sky at around sunset instead of midnight. Sirius is the brightest star in the constellation of Canis Major (the big dog). So, some other constellation will be prominently visible high in the sky at this later date.

? Exercise 2.4.1

If a star rises at 8:30 p.m. tonight, approximately what time will it rise two months from now?

Answer

In two months, the star will rise:
$60 \text{ days} \times \frac{4 \text{ minutes}}{\text{day}} = 240 \text{ minutes or } 4 \text{ hours earlier.}$
This means it will rise at 4:30 p.m.

Apparent Solar Time

We can define apparent solar time as time reckoned by the actual position of the Sun in the sky (or, during the night, its position below the horizon). This is the kind of time indicated by sundials, and it probably represents the earliest measure of time used by ancient civilizations. Today, we adopt the middle of the night as the starting point of the day and measure time in hours elapsed since midnight.

During the first half of the day, the Sun has not yet reached the meridian (the great circle in the sky that passes through our zenith). We designate those hours as before midday (*ante meridiem*, or a.m.), before the Sun reaches the local meridian. We customarily start numbering the hours after noon over again and designate them by p.m. (*post meridiem*), after the Sun reaches the local meridian.

Although apparent solar time seems simple, it is not really very convenient to use. The exact length of an apparent solar day varies slightly during the year. The eastward progress of the Sun in its annual journey around the sky is not uniform because the speed of Earth varies slightly in its elliptical orbit. Another complication is that Earth's axis of rotation is not perpendicular to the plane of its revolution. Thus, apparent solar time does not advance at a uniform rate. After the invention of mechanical clocks that run at a uniform rate, it became necessary to abandon the apparent solar day as the fundamental unit of time.

Mean Solar Time and Standard Time

Instead, we can consider the mean solar time, which is based on the average value of the solar day over the course of the year. A mean solar day contains exactly 24 hours and is what we use in our everyday timekeeping. Although mean solar time has the advantage of progressing at a uniform rate, it is still inconvenient for practical use because it is determined by the position of the Sun. For example, noon occurs when the Sun is highest in the sky on the meridian (but not necessarily at the zenith). But because we live on a round Earth, the exact time of noon is different as you change your longitude by moving east or west.

If mean solar time were strictly observed, people traveling east or west would have to reset their watches continually as the longitude changed, just to read the local mean time correctly. For instance, a commuter traveling from Oyster Bay on Long Island to New York City would have to adjust the time on the trip through the East River tunnel because Oyster Bay time is actually about 1.6 minutes more advanced than that of Manhattan. (Imagine an airplane trip in which an obnoxious flight attendant gets on the intercom every minute, saying, "Please reset your watch for local mean time.")

Until near the end of the nineteenth century, every city and town in the United States kept its own local mean time. With the development of railroads and the telegraph, however, the need for some kind of standardization became evident. In 1883, the United States was divided into four standard time zones (now six, including Hawaii and Alaska), each with one system of time within that zone.

By 1900, most of the world was using the system of 24 standardized global time zones. Within each zone, all places keep the same *standard time*, with the local mean solar time of a standard line of longitude running more or less through the middle of each zone. Now travelers reset their watches only when the time change has amounted to a full hour. Pacific standard time is 3 hours earlier

than eastern standard time, a fact that becomes painfully obvious in California when someone on the East Coast forgets and calls you at 5:00 a.m.

Globally, almost all countries have adopted one or more standard time zones, although one of the largest nations, India, has settled on a half-zone, being 5.5 hours from Greenwich standard. Also, China officially uses only one time zone, so all the clocks in that country keep the same time. In Tibet, for example, the Sun rises while the clocks (which keep Beijing time) say it is midmorning already.

Daylight saving time is simply the local standard time of the place plus 1 hour. It has been adopted for spring and summer use in most states in the United States, as well as in many countries, to prolong the sunlight into evening hours, on the apparent theory that it is easier to change the time by government action than it would be for individuals or businesses to adjust their own schedules to produce the same effect. It does not, of course, "save" any daylight at all—because the amount of sunlight is not determined by what we do with our clocks—and its observance is a point of legislative debate in some states.

The International Date Line

The fact that time is always advancing as you move toward the east presents a problem. Suppose you travel eastward around the world. You pass into a new time zone, on the average, about every 15° of longitude you travel, and each time you dutifully set your watch ahead an hour. By the time you have completed your trip, you have set your watch ahead a full 24 hours and thus gained a day over those who stayed at home.

The solution to this dilemma is the International Date Line, set by international agreement to run approximately along the 180° meridian of longitude. The date line runs down the middle of the Pacific Ocean, although it jogs a bit in a few places to avoid cutting through groups of islands and through Alaska (Figure 4.11). By convention, at the date line, the date of the calendar is changed by one day. Crossing the date line from west to east, thus advancing your time, you compensate by decreasing the date; crossing from east to west, you increase the date by one day. To maintain our planet on a rational system of timekeeping, we simply must accept that the date will differ in different cities at the same time. A good example is the date when the Imperial Japanese Navy bombed Pearl Harbor in Hawaii, known in the United States as Sunday, December 7, 1941, but taught to Japanese students as Monday, December 8.

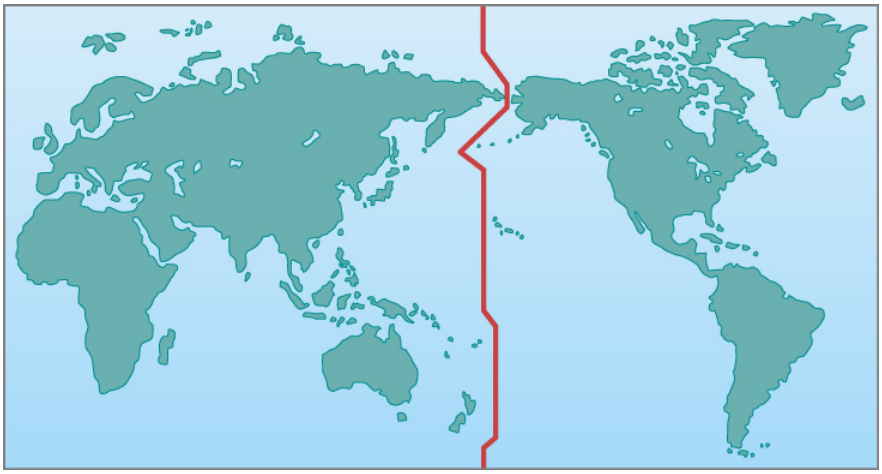


Figure 4.11 : Where the Date Changes. The International Date Line is an arbitrarily drawn line on Earth where the date changes. So that neighbors do not have different days, the line is located where Earth's surface is mostly water.

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2.5: The Calendar

Learning Objectives

By the end of this section, you will be able to:

- Understand how calendars varied among different cultures
- Explain the origins of our modern calendar

"What's today's date?" is one of the most common questions you can ask (usually when signing a document or worrying about whether you should have started studying for your next astronomy exam). Long before the era of digital watches, smartphones, and fitness bands that tell the date, people used calendars to help measure the passage of time.

The Challenge of the Calendar

There are two traditional functions of any calendar. First, it must keep track of time over the course of long spans, allowing people to anticipate the cycle of the seasons and to honor special religious or personal anniversaries. Second, to be useful to a large number of people, a calendar must use natural time intervals that everyone can agree on—those defined by the motions of Earth, the Moon, and sometimes even the planets. The natural units of our calendar are the *day*, based on the period of rotation of Earth; the *month*, based on the cycle of the Moon's phases (see later in this chapter) about Earth; and the year, based on the period of revolution of Earth about the Sun. Difficulties have resulted from the fact that these three periods are not commensurable; that's a fancy way of saying that one does not divide evenly into any of the others.

The rotation period of Earth is, by definition, 1.0000 day (and here the solar day is used, since that is the basis of human experience). The period required by the Moon to complete its cycle of phases, called the *month*, is 29.5306 days. The basic period of revolution of Earth, called the *tropical year*, is 365.2422 days. The ratios of these numbers are not convenient for calculations. This is the historic challenge of the calendar, dealt with in various ways by different cultures.

Early Calendars

Even the earliest cultures were concerned with the keeping of time and the calendar. Some interesting examples include monuments left by Bronze Age people in northwestern Europe, especially the British Isles. The best preserved of the monuments is Stonehenge, about 13 kilometers from Salisbury in southwest England (Figure 4.12). It is a complex array of stones, ditches, and holes arranged in concentric circles. Carbon dating and other studies show that Stonehenge was built during three periods ranging from about 2800 to 1500 BCE. Some of the stones are aligned with the directions of the Sun and Moon during their risings and settings at critical times of the year (such as the summer and winter solstices), and it is generally believed that at least one function of the monument was connected with the keeping of a calendar.



Figure 4.12 : Stonehenge. The ancient monument known as Stonehenge was used to keep track of the motions of the Sun and Moon. (credit: modification of work by Adriano Aurelio Araujo)

The Maya in Central America, who thrived more than a thousand years ago, were also concerned with the keeping of time. Their calendar was as sophisticated as, and perhaps more complex than, contemporary calendars in Europe. The Maya did not attempt to

correlate their calendar accurately with the length of the year or lunar month. Rather, their calendar was a system for keeping track of the passage of days and for counting time far into the past or future. Among other purposes, it was useful for predicting astronomical events, such as the position of Venus in the sky (Figure 4.13).



Figure 4.13 : El Caracol. This Mayan observatory at Chichen Itza in the Yucatan, Mexico, dates from around the year 1000. (credit: "wiredtourist.com"/Flickr)

The ancient Chinese developed an especially complex calendar, largely limited to a few privileged hereditary court astronomer-astrologers. In addition to the motions of Earth and the Moon, they were able to fit in the approximately 12-year cycle of Jupiter, which was central to their system of astrology. The Chinese still preserve some aspects of this system in their cycle of 12 "years"—the Year of the Dragon, the Year of the Pig, and so on—that are defined by the position of Jupiter in the zodiac.

Our Western calendar derives from a long history of timekeeping beginning with the Sumerians, dating back to at least the second millennium BCE, and continuing with the Egyptians and the Greeks around the eighth century BCE. These calendars led, eventually, to the *Julian calendar*, introduced by Julius Caesar, which approximated the year at 365.25 days, fairly close to the actual value of 365.2422. The Romans achieved this approximation by declaring years to have 365 days each, with the exception of every fourth year. The *leap year* was to have one extra day, bringing its length to 366 days, and thus making the average length of the year in the Julian calendar 365.25 days.

In this calendar, the Romans had dropped the almost impossible task of trying to base their calendar on the Moon as well as the Sun, although a vestige of older lunar systems can be seen in the fact that our months have an average length of about 30 days. However, lunar calendars remained in use in other cultures, and Islamic calendars, for example, are still primarily lunar rather than solar.

The Gregorian Calendar

Although the Julian calendar (which was adopted by the early Christian Church) represented a great advance, its average year still differed from the true year by about 11 minutes, an amount that accumulates over the centuries to an appreciable error. By 1582, that 11 minutes per year had added up to the point where the first day of spring was occurring on March 11, instead of March 21. If the trend were allowed to continue, eventually the Christian celebration of Easter would be occurring in early winter. Pope Gregory XIII, a contemporary of Galileo, felt it necessary to institute further calendar reform.

The Gregorian calendar reform consisted of two steps. First, 10 days had to be dropped out of the calendar to bring the vernal equinox back to March 21; by proclamation, the day following October 4, 1582, became October 15. The second feature of the new Gregorian calendar was a change in the rule for leap year, making the average length of the year more closely approximate the tropical year. Gregory decreed that three of every four century years—all leap years under the Julian calendar—would be common years henceforth. The rule was that only century years divisible by 400 would be leap years. Thus, 1700, 1800, and 1900—all divisible by 4 but not by 400—were not leap years in the Gregorian calendar. On the other hand, the years 1600 and 2000, both divisible by 400, were leap years. The average length of this Gregorian year, 365.2425 mean solar days, is correct to about 1 day in 3300 years.

The Catholic countries immediately put the Gregorian reform into effect, but countries of the Eastern Church and most Protestant countries did not adopt it until much later. It was 1752 when England and the American colonies finally made the change. By parliamentary decree, September 2, 1752, was followed by September 14. Although special laws were passed to prevent such abuses as landlords collecting a full month's rent for September, there were still riots, and people demanded their 12 days back. Russia did not abandon the Julian calendar until the time of the Bolshevik revolution. The Russians then had to omit 13 days to

come into step with the rest of the world. The anniversary of the October Revolution (old calendar) of 1917, bringing the communists to power, thus ended up being celebrated in November (new calendar), a difference that is perhaps not so important since the fall of communism.

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2.6: Phases and Motions of the Moon

Learning Objectives

By the end of this section, you will be able to:

- Explain the cause of the lunar phases
- Understand how the Moon rotates and revolves around Earth

After the Sun, the Moon is the brightest and most obvious object in the sky. Unlike the Sun, it does not shine under its own power, but merely glows with reflected sunlight. If you were to follow its progress in the sky for a month, you would observe a cycle of phases (different appearances), with the Moon starting dark and getting more and more illuminated by sunlight over the course of about two weeks. After the Moon's disk becomes fully bright, it begins to fade, returning to dark about two weeks later.

These changes fascinated and mystified many early cultures, which came up with marvelous stories and legends to explain the cycle of the Moon. Even in the modern world, many people don't understand what causes the phases, thinking that they are somehow related to the shadow of Earth. Let us see how the phases can be explained by the motion of the Moon relative to the bright light source in the solar system, the Sun.

Lunar Phases

Although we know that the Sun moves 1/12 of its path around the sky each month, for purposes of explaining the phases, we can assume that the Sun's light comes from roughly the same direction during the course of a four-week lunar cycle. The Moon, on the other hand, moves completely around Earth in that time. As we watch the Moon from our vantage point on Earth, how much of its face we see illuminated by sunlight depends on the angle the Sun makes with the Moon.

Here is a simple experiment to show you what we mean: stand about 6 feet in front of a bright electric light in a completely dark room (or outdoors at night) and hold in your hand a small round object such as a tennis ball or an orange. Your head can then represent Earth, the light represents the Sun, and the ball the Moon. Move the ball around your head (making sure you don't cause an eclipse by blocking the light with your head). You will see phases just like those of the Moon on the ball. (Another good way to get acquainted with the phases and motions of the Moon is to follow our satellite in the sky for a month or two, recording its shape, its direction from the Sun, and when it rises and sets.)

Let's examine the Moon's cycle of phases using Figure 4.14, which depicts the Moon's behavior for the entire month. The trick to this figure is that you must imagine yourself standing on Earth, facing the Moon in each of its phases. So, for the position labeled "New," you are on the right side of Earth and it's the middle of the day; for the position "Full," you are on the left side of Earth in the middle of the night. Note that in every position on Figure 4.14, the Moon is half illuminated and half dark (as a ball in sunlight should be). The difference at each position has to do with what part of the Moon faces Earth.

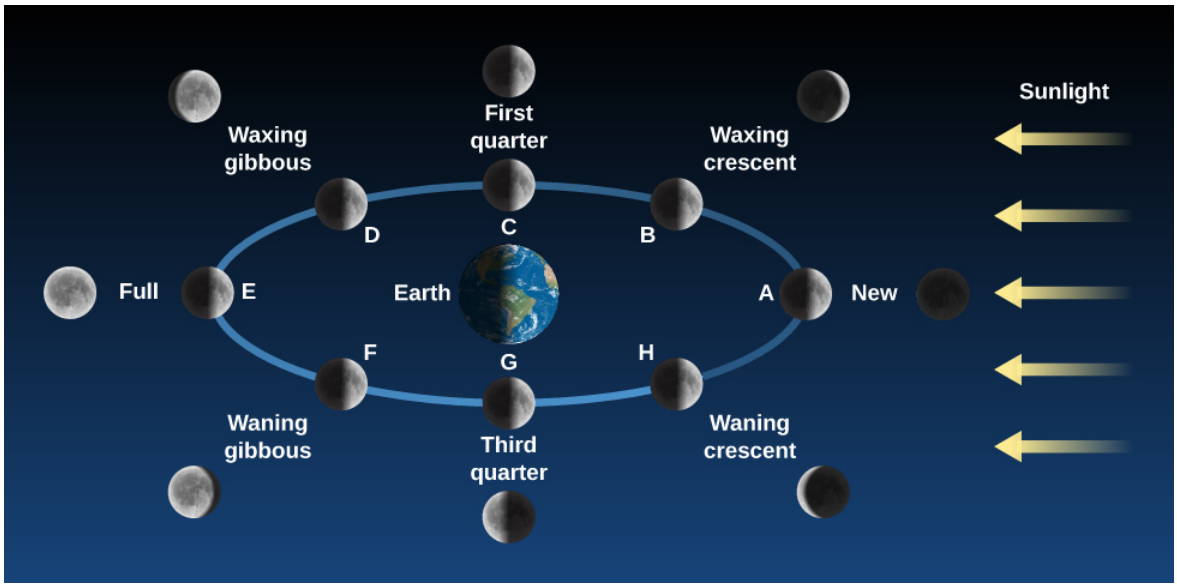


Figure 4.14 : Phases of the Moon. The appearance of the Moon changes over the course of a complete monthly cycle. The pictures of the Moon on the white circle show the perspective from space, with the Sun off to the right in a fixed position. The outer images show how the Moon appears to you in the sky from each point in the orbit. Imagine yourself standing on Earth, facing the Moon at each stage. In the position "New," for example, you are facing the Moon from the right side of Earth in the middle of the day. (Note that the distance of the Moon from Earth is not to scale in this diagram: the Moon is roughly 30 Earth-diameters away from us.) (credit: modification of work by NASA)

The Moon is said to be *new* when it is in the same general direction in the sky as the Sun (position A). Here, its illuminated (bright) side is turned away from us and its dark side is turned toward us. You might say that the Sun is shining on the "wrong " side of the Moon from our perspective. In this phase the Moon is invisible to us; its dark, rocky surface does not give off any light of its own. Because the new moon is in the same part of the sky as the Sun, it rises at sunrise and sets at sunset.

But the Moon does not remain in this phase long because it moves eastward each day in its monthly path around us. Since it takes about 30 days to orbit Earth and there are 360° in a circle, the Moon will move about 12° in the sky each day (or about 24 times its own diameter). A day or two after the new phase, the thin *crescent* first appears, as we begin to see a small part of the Moon's illuminated hemisphere. It has moved into a position where it now reflects a little sunlight toward us along one side. The bright crescent increases in size on successive days as the Moon moves farther and farther around the sky away from the direction of the Sun (position B). Because the Moon is moving eastward away from the Sun, it rises later and later each day (like a student during summer vacation).

After about one week, the Moon is one-quarter of the way around its orbit (position C) and so we say it is at the *first quarter* phase. Half of the Moon's illuminated side is visible to Earth observers. Because of its eastward motion, the Moon now lags about one-quarter of the day behind the Sun, rising around noon and setting around midnight.

During the week after the first quarter phase, we see more and more of the Moon's illuminated hemisphere (position D), a phase that is called *waxing* (or growing) gibbous (from the Latin *gibbus*, meaning hump). Eventually, the Moon arrives at position E in our figure, where it and the Sun are opposite each other in the sky. The side of the Moon turned toward the Sun is also turned toward Earth, and we have the *full* phase.

When the Moon is full, it is opposite the Sun in the sky. The Moon does the opposite of what the Sun does, rising at sunset and setting at sunrise. Note what that means in practice: the completely illuminated (and thus very noticeable) Moon rises just as it gets dark, remains in the sky all night long, and sets as the Sun's first rays are seen at dawn. Its illumination throughout the night helps lovers on a romantic stroll and students finding their way back to their dorms after a long night in the library or an off-campus party.

And when is the full moon highest in the sky and most noticeable? At midnight, a time made famous in generations of horror novels and films. (Note how the behavior of a vampire like Dracula parallels the behavior of the full Moon: Dracula rises at sunset, does his worst mischief at midnight, and must be back down in his coffin by sunrise. The old legends were a way of personifying the behavior of the Moon, which was a much more dramatic part of people's lives in the days before electric lights and television.)

Folklore has it that more crazy behavior is seen during the time of the full moon (the Moon even gives a name to crazy behavior—"lunacy"). But, in fact, statistical tests of this "hypothesis" involving thousands of records from hospital emergency rooms and police files do not reveal any correlation of human behavior with the phases of the Moon. For example, homicides occur at the same rate during the new moon or the crescent moon as during the full moon. Most investigators believe that the real story is not that more crazy behavior happens on nights with a full moon, but rather that we are more likely to notice or remember such behavior with the aid of a bright celestial light that is up all night long.

During the two weeks following the full moon, the Moon goes through the same phases again in reverse order (points F, G, and H in Figure 4.14), returning to new phase after about 29.5 days. About a week after the full moon, for example, the Moon is at *third quarter*, meaning that it is three-quarters of the way around (not that it is three-quarters illuminated—in fact, half of the visible side of the Moon is again dark). At this phase, the Moon is now rising around midnight and setting around noon.

Note that there is one thing quite misleading about Figure 4.14. If you look at the Moon in position E, although it is full in theory, it appears as if its illumination would in fact be blocked by a big fat Earth, and hence we would not see anything on the Moon except Earth's shadow. In reality, the Moon is nowhere near as close to Earth (nor is its path so identical with the Sun's in the sky) as this diagram (and the diagrams in most textbooks) might lead you to believe.

The Moon is actually 30 *Earth-diameters* away from us; Science and the Universe: A Brief Tour contains a diagram that shows the two objects to scale. And, since the Moon's orbit is tilted relative to the path of the Sun in the sky, Earth's shadow misses the Moon most months. That's why we regularly get treated to a full moon. The times when Earth's shadow does fall on the Moon are called lunar eclipses and are discussed in Eclipses of the Sun and Moon.

Making Connections: Astronomy and the Days of the Week

The week seems independent of celestial motions, although its length may have been based on the time between quarter phases of the Moon. In Western culture, the seven days of the week are named after the seven "wanderers" that the ancients saw in the sky: the Sun, the Moon, and the five planets visible to the unaided eye (Mercury, Venus, Mars, Jupiter, and Saturn).

In English, we can easily recognize the names Sun-day (Sunday), Moon-day (Monday), and Saturn-day (Saturday), but the other days are named after the Norse equivalents of the Roman gods that gave their names to the planets. In languages more directly related to Latin, the correspondences are clearer. Wednesday, Mercury's day, for example, is *mercoledi* in Italian, *mercredi* in French, and *miércoles* in Spanish. Mars gives its name to Tuesday (*martes* in Spanish), Jupiter or Jove to Thursday (*giovedi* in Italian), and Venus to Friday (*vendredi* in French).

There is no reason that the week has to have seven days rather than five or eight. It is interesting to speculate that if we had lived in a planetary system where more planets were visible without a telescope, the Beatles could have been right and we might well have had "Eight Days a Week."

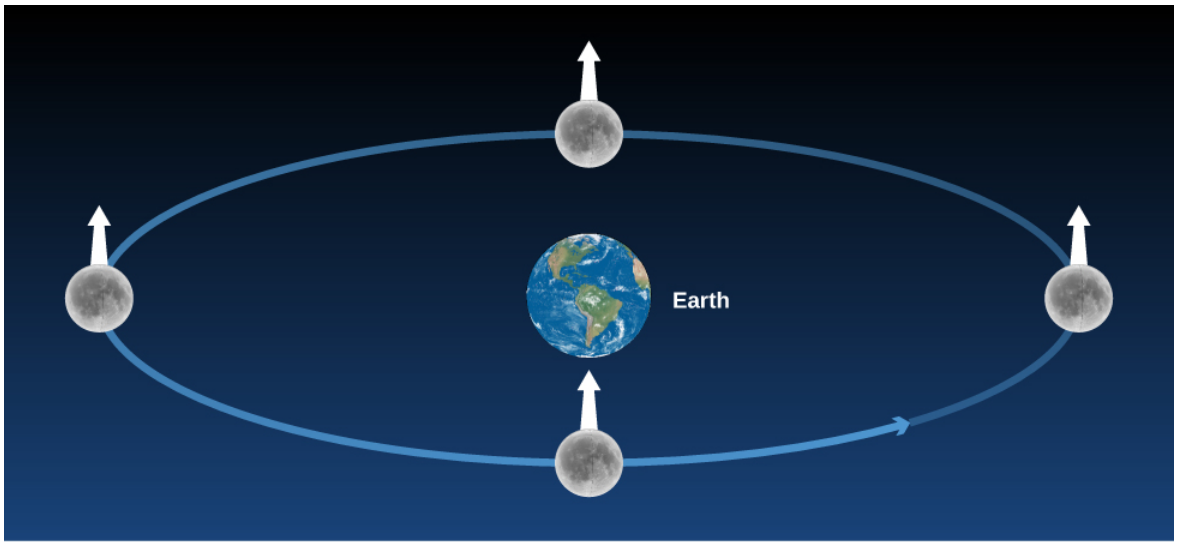
Link to Learning

This simulation of the Moon orbiting the Earth shows both a "top-down" view and the view from Earth's surface.

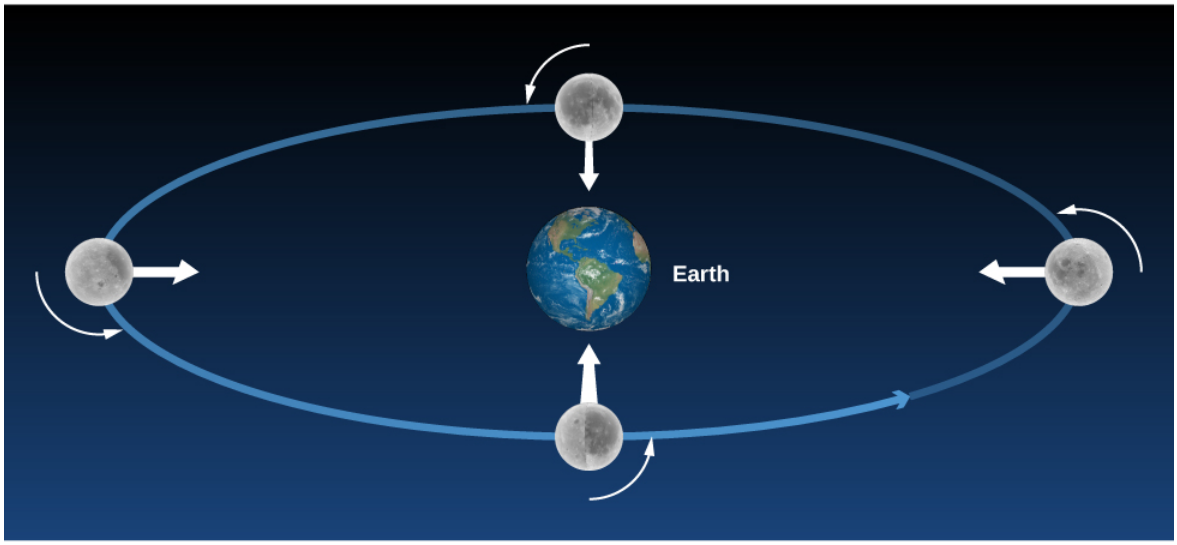
The Moon's Revolution and Rotation

The Moon's sidereal period—that is, the period of its revolution about Earth measured with respect to the stars—is a little over 27 days: the sidereal month is 27.3217 days to be exact. The time interval in which the phases repeat—say, from full to full—is the solar month, 29.5306 days. The difference results from Earth's motion around the Sun. The Moon must make more than a complete turn around the moving Earth to get back to the same phase with respect to the Sun. As we saw, the Moon changes its position on the celestial sphere rather rapidly: even during a single evening, the Moon creeps visibly eastward among the stars, traveling its own width in a little less than 1 hour. The delay in moonrise from one day to the next caused by this eastward motion averages about 50 minutes.

The Moon *rotates* on its axis in exactly the same time that it takes to *revolve* about Earth. As a consequence, the Moon always keeps the same face turned toward Earth (Figure 4.15). You can simulate this yourself by "orbiting" your roommate or another volunteer. Start by facing your roommate. If you make one rotation (spin) with your shoulders in the exact same time that you revolve around him or her, you will continue to face your roommate during the whole "orbit." As we will see in coming chapters, our Moon is not the only world that exhibits this behavior, which scientists call synchronous rotation.



(a)



(b)

Figure 4.15 : The Moon without and with Rotation. In this figure, we stuck a white arrow into a fixed point on the Moon to keep track of its sides. (a) If the Moon did not rotate as it orbited Earth, it would present all of its sides to our view; hence the white arrow would point directly toward Earth only in the bottom position on the diagram. (b) Actually, the Moon rotates in the same period that it revolves, so we always see the same side (the white arrow keeps pointing to Earth).

The differences in the Moon's appearance from one night to the next are due to changing illumination by the Sun, not to its own rotation. You sometimes hear the back side of the Moon (the side we never see) called the "dark side." This is a misunderstanding of the real situation: which side is light and which is dark changes as the Moon moves around Earth. The back side is dark no more frequently than the front side. Since the Moon rotates, the Sun rises and sets on all sides of the Moon. With apologies to Pink Floyd, there is simply no regular "Dark Side of the Moon."

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2.7: Ocean Tides and the Moon

Learning Objectives

By the end of this section, you will be able to:

- Describe what causes tides on Earth
- Explain why the amplitude of tides changes during the course of a month

Anyone living near the sea is familiar with the twice-daily rising and falling of the tides. Early in history, it was clear that tides must be related to the Moon because the daily delay in high tide is the same as the daily delay in the Moon's rising. A satisfactory explanation of the tides, however, awaited the theory of gravity, supplied by Newton.

The Pull of the Moon on Earth

The gravitational forces exerted by the Moon at several points on Earth are illustrated in Figure 4.16. These forces differ slightly from one another because Earth is not a point, but has a certain size: all parts are not equally distant from the Moon, nor are they all in exactly the same direction from the Moon. Moreover, Earth is not perfectly rigid. As a result, the differences among the forces of the Moon's attraction on different parts of Earth (called *differential forces*) cause Earth to distort slightly. The side of Earth nearest the Moon is attracted toward the Moon more strongly than is the center of Earth, which in turn is attracted more strongly than is the side opposite the Moon. Thus, the differential forces tend to stretch Earth slightly into an *oblate spheroid* (which is something like an American football shape), with its long diameter pointed toward the Moon.

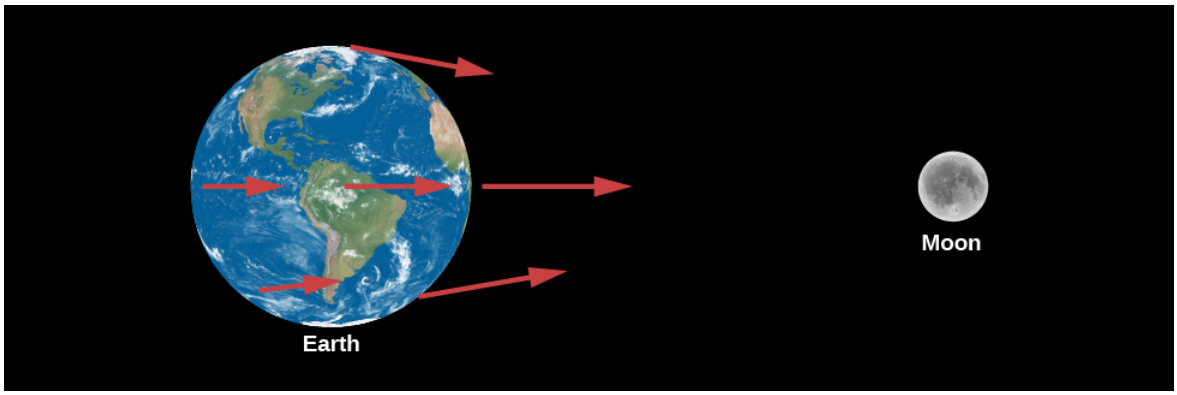


Figure 4.16 : Pull of the Moon. The Moon's differential attraction is shown on different parts of Earth. (Note that the differences have been exaggerated for educational purposes.)

If Earth were made of water, it would distort until the Moon's differential forces over different parts of its surface came into balance with Earth's own gravitational forces pulling it together. Calculations show that in this case, Earth would distort from a sphere by amounts ranging up to nearly 1 meter. Measurements of the actual deformation of Earth show that the solid Earth does distort, but only about one-third as much as water would, because of the greater rigidity of Earth's interior.

Because the tidal distortion of the solid Earth amounts—at its greatest—to only about 20 centimeters, Earth does not distort enough to balance the Moon's differential forces with its own gravity. Hence, objects at Earth's surface experience tiny horizontal tugs, tending to make them slide about. These *tide-raising forces* are too insignificant to affect solid objects like astronomy students or rocks in Earth's crust, but they do affect the waters in the oceans.

The Formation of Tides

The tide-raising forces, acting over a number of hours, produce motions of the water that result in measurable tidal bulges in the oceans. Water on the side of Earth facing the Moon flows toward it, with the greatest depths roughly at the point below the Moon. On the side of Earth opposite the Moon, water also flows to produce a tidal bulge (Figure 4.17).

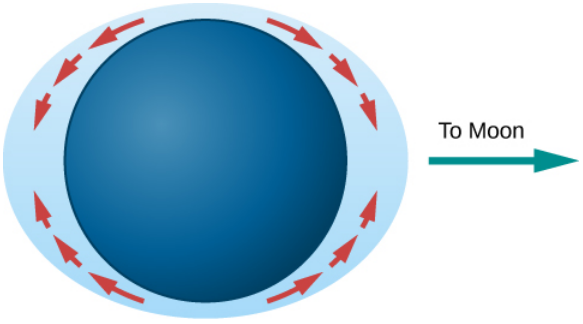


Figure 4.17 : Tidal Bulges in an “Ideal” Ocean. Differences in gravity cause tidal forces that push water in the direction of tidal bulges on Earth.

Link to Learning

You can run this animation for a visual demonstration of the tidal bulge.

Note that the tidal bulges in the oceans do not result from the Moon’s compressing or expanding the water, nor from the Moon’s lifting the water “away from Earth.” Rather, they result from an actual flow of water over Earth’s surface toward the two regions below and opposite the Moon, causing the water to pile up to greater depths at those places (Figure 4.18).



Figure 4.18 : High and Low Tides. This is a side-by-side comparison of the Bay of Fundy in Canada at high and low tides. (credit a, b: modification of work by Dylan Kereluk)

In the idealized (and, as we shall see, oversimplified) model just described, the height of the tides would be only a few feet. The rotation of Earth would carry an observer at any given place alternately into regions of deeper and shallower water. An observer being carried toward the regions under or opposite the Moon, where the water was deepest, would say, “The tide is coming in”; when carried away from those regions, the observer would say, “The tide is going out.” During a day, the observer would be carried through two tidal bulges (one on each side of Earth) and so would experience two high tides and two low tides.

The Sun also produces tides on Earth, although it is less than half as effective as the Moon at tide raising. The actual tides we experience are a combination of the larger effect of the Moon and the smaller effect of the Sun. When the Sun and Moon are lined up (at new moon or full moon), the tides produced reinforce each other and so are greater than normal (Figure 4.19). These are called spring tides (the name is connected not to the season but to the idea that higher tides “spring up”). Spring tides are approximately the same, whether the Sun and Moon are on the same or opposite sides of Earth, because tidal bulges occur on both sides. When the Moon is at first quarter or last quarter (at right angles to the Sun’s direction), the tides produced by the Sun partially cancel the tides of the Moon, making them lower than usual. These are called neap tides.

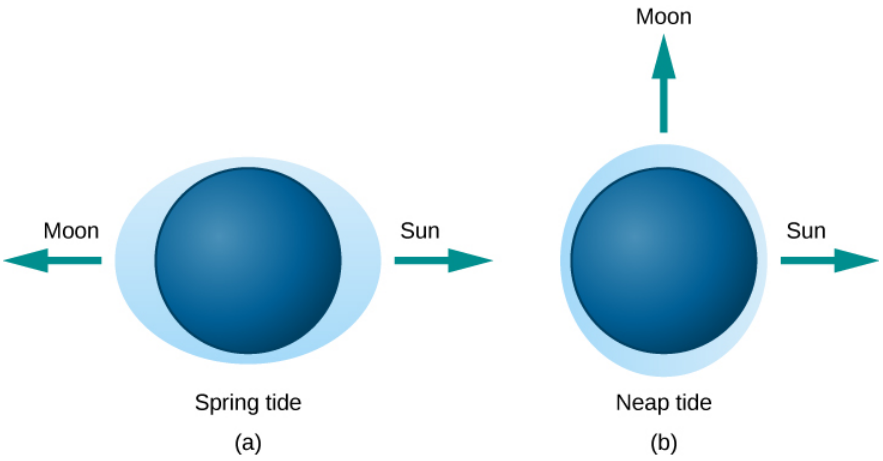


Figure 4.19 : Tides Caused by Different Alignments of the Sun and Moon. (a) In spring tides, the Sun's and Moon's pulls reinforce each other. (b) In neap tides, the Sun and the Moon pull at right angles to each other and the resulting tides are lower than usual.

The "simple" theory of tides, described in the preceding paragraphs, would be sufficient if Earth rotated very slowly and were completely surrounded by very deep oceans. However, the presence of land masses stopping the flow of water, the friction in the oceans and between oceans and the ocean floors, the rotation of Earth, the wind, the variable depth of the ocean, and other factors all complicate the picture. This is why, in the real world, some places have very small tides while in other places huge tides become tourist attractions. If you have been in such places, you may know that "tide tables" need to be computed and published for each location; one set of tide predictions doesn't work for the whole planet. In this introductory chapter, we won't delve further into these complexities.

Voyagers in Astronomy: George Darwin and the Slowing of Earth

The rubbing of water over the face of Earth involves an enormous amount of energy. Over long periods of time, the friction of the tides is slowing down the rotation of Earth. Our day gets longer by about 0.002 second each century. That seems very small, but such tiny changes can add up over millions and billions of years.

Although Earth's spin is slowing down, the angular momentum (see Orbits and Gravity) in a system such as the Earth-Moon system cannot change. Thus, some other spin motion must speed up to take the extra angular momentum. The details of what happens were worked out over a century ago by George Darwin, the son of naturalist Charles Darwin. George Darwin (see Figure 4.20) had a strong interest in science but studied law for six years and was admitted to the bar. However, he never practiced law, returning to science instead and eventually becoming a professor at Cambridge University. He was a protégé of Lord Kelvin, one of the great physicists of the nineteenth century, and he became interested in the long-term evolution of the solar system. He specialized in making detailed (and difficult) mathematical calculations of how orbits and motions change over geologic time.

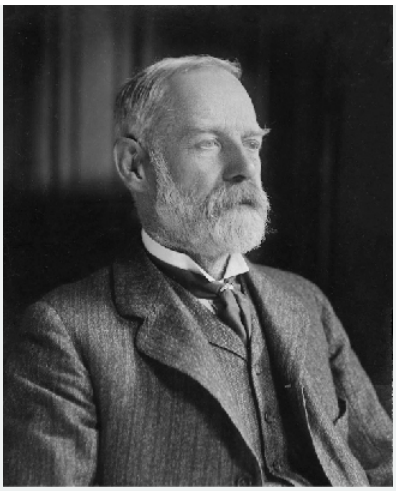


Figure 4.20 : George Darwin (1845–1912). George Darwin is best known for studying Earth's spin in relation to angular momentum.

What Darwin calculated for the Earth-Moon system was that the Moon will slowly spiral outward, away from Earth. As it moves farther away, it will orbit less quickly (just as planets farther from the Sun move more slowly in their orbits). Thus, the month will get longer. Also, because the Moon will be more distant, total eclipses of the Sun will no longer be visible from Earth.

Both the day and the month will continue to get longer, although bear in mind that the effects are very gradual. Darwin's calculations were confirmed by mirrors placed on the Moon by Apollo 11 astronauts. These show that the Moon is moving away by 3.8 centimeters per year, and that ultimately—billions of years in the future—the day and the month will be the same length (about 47 of our present days). At this point the Moon will be stationary in the sky over the same spot on Earth, meaning some parts of Earth will see the Moon and its phases and other parts will never see them. This kind of alignment is already true for Pluto's moon Charon (among others). Its rotation and orbital period are the same length as a day on Pluto.

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2.8: Eclipses of the Sun and Moon

Learning Objectives

By the end of this section, you will be able to:

- Describe what causes lunar and solar eclipses
- Differentiate between a total and partial solar eclipse
- Explain why lunar eclipses are much more common than solar eclipses

One of the coincidences of living on Earth at the present time is that the two most prominent astronomical objects, the Sun and the Moon, have nearly the same apparent size in the sky. Although the Sun is about 400 times larger in diameter than the Moon, it is also about 400 times farther away, so both the Sun and the Moon have the same angular size—about 1/2°. As a result, the Moon, as seen from Earth, can appear to cover the Sun, producing one of the most impressive events in nature.

Any solid object in the solar system casts a shadow by blocking the light of the Sun from a region behind it. This shadow in space becomes apparent whenever another object moves into it. In general, an *eclipse* occurs whenever any part of either Earth or the Moon enters the shadow of the other. When the Moon's shadow strikes Earth, people within that shadow see the Sun at least partially covered by the Moon; that is, they witness a solar eclipse. When the Moon passes into the shadow of Earth, people on the night side of Earth see the Moon darken in what is called a lunar eclipse. Let's look at how these happen in more detail.

The shadows of Earth and the Moon consist of two parts: a cone where the shadow is darkest, called the *umbra*, and a lighter, more diffuse region of darkness called the *penumbra*. As you can imagine, the most spectacular eclipses occur when an object enters the umbra. Figure 4.21 illustrates the appearance of the Moon's shadow and what the Sun and Moon would look like from different points within the shadow.

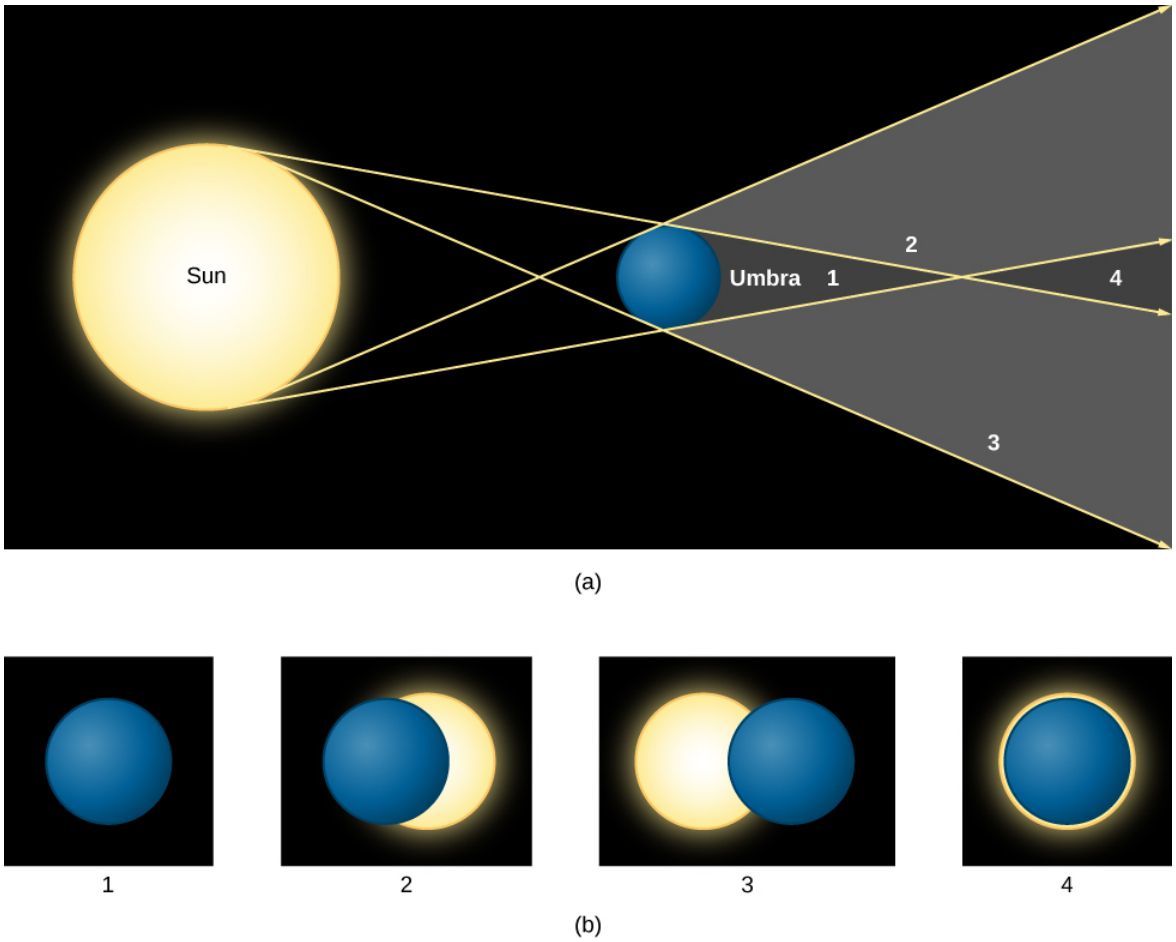


Figure 4.21 : Solar Eclipse. (a) The shadow cast by a spherical body (the Moon, for example) is shown. Notice the dark umbra and the lighter penumbra. Four points in the shadow are labeled with numbers. In (b) you see what the Sun and Moon would look like in the sky at the four labeled points. At position 1, you see a total eclipse. At positions 2 and 3, the eclipse is partial. At position 4, the Moon is farther away and thus cannot cover the Sun completely; a ring of light thus shows around the Sun, creating what is called an "annular" eclipse.

If the path of the Moon in the sky were identical to the path of the Sun (the ecliptic), we might expect to see an eclipse of the Sun and the Moon each month—whenever the Moon got in front of the Sun or into the shadow of Earth. However, as we mentioned, the Moon's orbit is tilted relative to the plane of Earth's orbit about the Sun by about 5° (imagine two hula hoops with a common center, but tilted a bit). As a result, during most months, the Moon is sufficiently above or below the ecliptic plane to avoid an eclipse. But when the two paths cross (twice a year), it is then "eclipse season" and eclipses are possible.

Eclipses of the Sun

The apparent or angular sizes of both the Sun and Moon vary slightly from time to time as their distances from Earth vary. (Figure 4.21 shows the distance of the observer varying at points 1–4, but the idea is the same.) Much of the time, the Moon looks slightly smaller than the Sun and cannot cover it completely, even if the two are perfectly aligned. In this type of "annular eclipse," there is a ring of light around the dark sphere of the Moon.

However, if an eclipse of the Sun occurs when the Moon is somewhat nearer than its average distance, the Moon can completely hide the Sun, producing a *total* solar eclipse. Another way to say it is that a total eclipse of the Sun occurs at those times when the umbra of the Moon's shadow reaches the surface of Earth.

The geometry of a total solar eclipse is illustrated in Figure 4.22. If the Sun and Moon are properly aligned, then the Moon's darkest shadow intersects the ground at a small point on Earth's surface. Anyone on Earth within the small area covered by the tip of the Moon's shadow will, for a few minutes, be unable to see the Sun and will witness a total eclipse. At the same time, observers on a larger area of Earth's surface who are in the penumbra will see only a part of the Sun eclipsed by the Moon: we call this a *partial* solar eclipse.

Between Earth's rotation and the motion of the Moon in its orbit, the tip of the Moon's shadow sweeps eastward at about 1500 kilometers per hour along a thin band across the surface of Earth. The thin zone across Earth within which a total solar eclipse is visible (weather permitting) is called the eclipse path. Within a region about 3000 kilometers on either side of the eclipse path, a partial solar eclipse is visible. It does not take long for the Moon's shadow to sweep past a given point on Earth. The duration of totality may be only a brief instant; it can never exceed about 7 minutes.

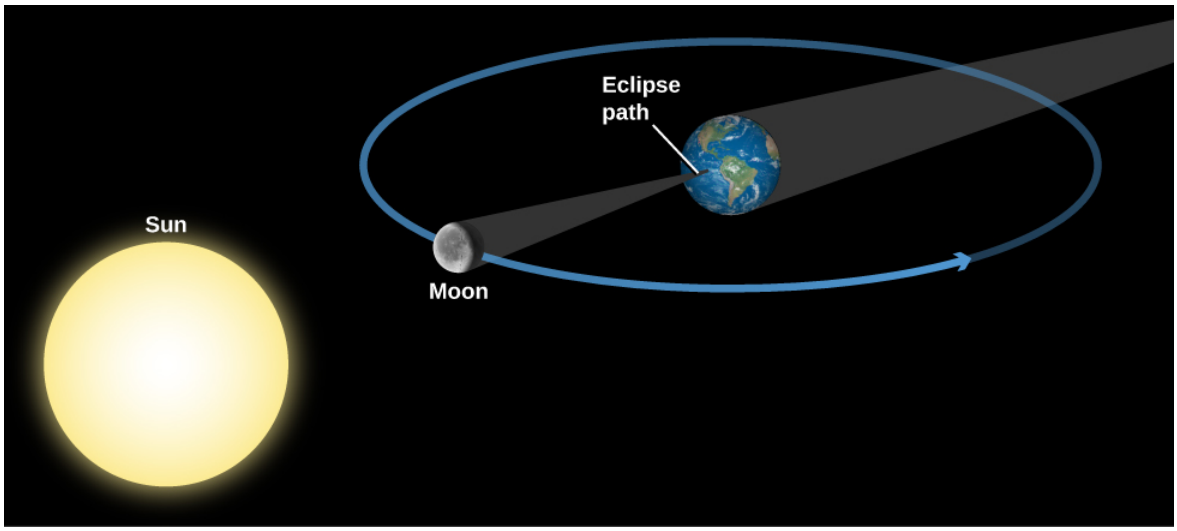


Figure 4.22 : Geometry of a Total Solar Eclipse. Note that our diagram is not to scale. The Moon blocks the Sun during new moon phase as seen from some parts of Earth and casts a shadow on our planet.

Because a total eclipse of the Sun is so spectacular, it is well worth trying to see one if you can. There are some people whose hobby is "eclipse chasing" and who brag about how many they have seen in their lifetimes. Because much of Earth's surface is water, eclipse chasing can involve lengthy boat trips (and often requires air travel as well). As a result, eclipse chasing is rarely within the budget of a typical college student. Nevertheless, a list of future eclipses is given for your reference in Appendix H, just in case you strike it rich early. (And, as you can see in the Appendix, there was a total eclipse visible in the United States in 2017, and there will be another in 2024, to which college students may be able to afford travel.)

Appearance of a Total Eclipse

What can you see if you are lucky enough to catch a total eclipse? A solar eclipse starts when the Moon just begins to silhouette itself against the edge of the Sun's disk. A partial phase follows, during which more and more of the Sun is covered by the Moon. About an hour after the eclipse begins, the Sun becomes completely hidden behind the Moon. In the few minutes immediately before this period of totality begins, the sky noticeably darkens, some flowers close up, and chickens may go to roost. As an eerie twilight suddenly descends during the day, other animals (and people) may get disoriented. During totality, the sky is dark enough that planets become visible in the sky, and usually the brighter stars do as well.

As the bright disk of the Sun becomes entirely hidden behind the Moon, the Sun's remarkable corona flashes into view (Figure 4.23). The *corona* is the Sun's outer atmosphere, consisting of sparse gases that extend for millions of miles in all directions from the apparent surface of the Sun. It is ordinarily not visible because the light of the corona is feeble compared with the light from the underlying layers of the Sun. Only when the brilliant glare from the Sun's visible disk is blotted out by the Moon during a total eclipse is the pearly white corona visible. (We'll talk more about the corona in the chapter on The Sun: A Garden-Variety Star.)



Figure 4.23 : The Sun's Corona. The corona (thin outer atmosphere) of the Sun is visible during a total solar eclipse. (It looks more extensive in photographs than it would to the unaided eye.) (credit: modification of work by Lutfar Rahman Nirjhar)

The total phase of the eclipse ends, as abruptly as it began, when the Moon begins to uncover the Sun. Gradually, the partial phases of the eclipse repeat themselves, in reverse order, until the Moon has completely uncovered the Sun. We should make one important safety point here: while the few minutes of the *total* eclipse are safe to look at, if any part of the Sun is uncovered, you must protect your eyes with safe eclipse glasses[2] or by projecting an image of the Sun (instead of looking at it directly). For more, read the How to Observe Solar Eclipses box in this chapter.

Eclipses of the Moon

A lunar eclipse occurs when the Moon enters the shadow of Earth. The geometry of a lunar eclipse is shown in Figure 4.24. Earth's dark shadow is about 1.4 million kilometers long, so at the Moon's distance (an average of 384,000 kilometers), it could cover about four full moons. Unlike a solar eclipse, which is visible only in certain local areas on Earth, a lunar eclipse is visible to everyone who can see the Moon. Because a lunar eclipse can be seen (weather permitting) from the entire night side of Earth, lunar eclipses are observed far more frequently from a given place on Earth than are solar eclipses.

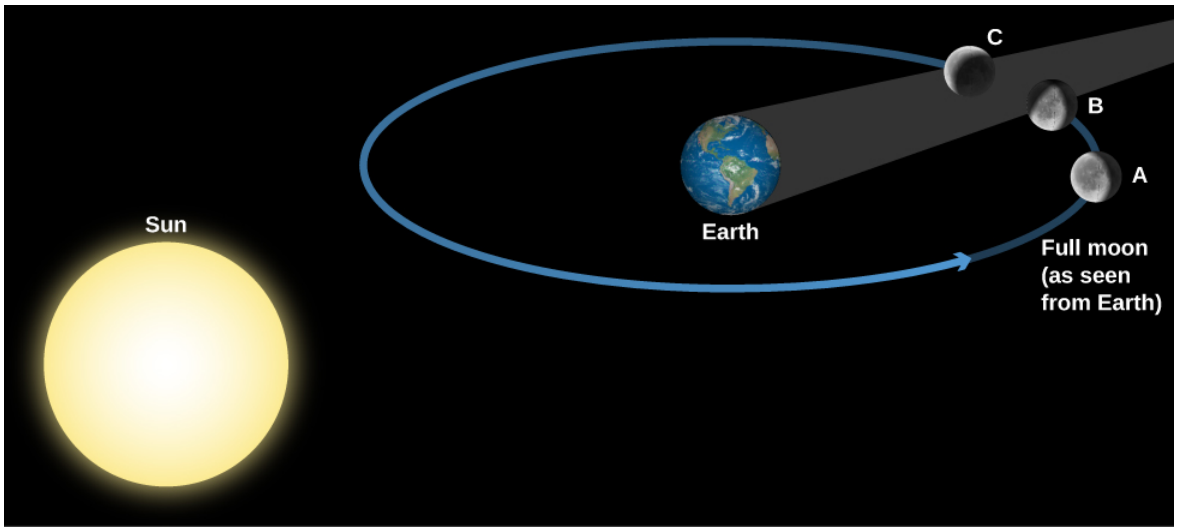


Figure 4.24 : Geometry of a Lunar Eclipse. The Moon is shown moving through the different parts of Earth's shadow during a total lunar eclipse. Note that the distance the Moon moves in its orbit during the eclipse has been exaggerated here for clarity.

An eclipse of the Moon is total only if the Moon's path carries it though Earth's umbra. If the Moon does not enter the umbra completely, we have a partial eclipse of the Moon. But because Earth is larger than the Moon, its umbra is larger, so that lunar eclipses last longer than solar eclipses, as we will discuss below.

A lunar eclipse can take place only when the Sun, Earth, and Moon are in a line. The Moon is opposite the Sun, which means the Moon will be in full phase before the eclipse, making the darkening even more dramatic. About 20 minutes before the Moon reaches the dark shadow, it dims somewhat as Earth partly blocks the sunlight. As the Moon begins to dip into the shadow, the curved shape of Earth's shadow upon it soon becomes apparent.

Even when totally eclipsed, the Moon is still faintly visible, usually appearing a dull coppery red. The illumination on the eclipsed Moon is sunlight that has been bent into Earth's shadow by passing through Earth's atmosphere.

After totality, the Moon moves out of the shadow and the sequence of events is reversed. The total duration of the eclipse depends on how closely the Moon's path approaches the axis of the shadow. For an eclipse where the Moon goes through the center of Earth's shadow, each partial phase consumes at least 1 hour, and totality can last as long as 1 hour and 40 minutes. Eclipses of the Moon are much more "democratic" than solar eclipses. Since the full moon is visible on the entire night side of Earth, the lunar eclipse is visible for all those who live in that hemisphere. (Recall that a total eclipse of the Sun is visible only in a narrow path where the shadow of the umbra falls.) Total eclipses of the Moon occur, on average, about once every two or three years. A list of future total eclipses of the Moon is in Appendix H. In addition, since the lunar eclipse happens to a full moon, and a full moon is not dangerous to look at, everyone can look at the Moon during all the parts of the eclipse without worrying about safety.

Thanks to our understanding of gravity and motion (see Orbits and Gravity), eclipses can now be predicted centuries in advance. We've come a long way since humanity stood frightened by the darkening of the Sun or the Moon, fearing the displeasure of the gods. Today, we enjoy the sky show with a healthy appreciation of the majestic forces that keep our solar system running.

Use the Solar and Lunar Eclipse simulation to explore the conditions of solar and lunar eclipses yourself.

Seeing for Yourself: How to Observe Solar Eclipses

A total eclipse of the Sun is a spectacular sight and should not be missed. However, it is extremely dangerous to look directly at the Sun: even a brief exposure can damage your eyes. Normally, few rational people are tempted to do this because it is painful (and something your mother told you never to do!). But during the partial phases of a solar eclipse, the temptation to take a look is strong. Think before you give in. The fact that the Moon is covering part of the Sun doesn't make the uncovered part any less dangerous to look at. Still, there are perfectly safe ways to follow the course of a solar eclipse, if you are lucky enough to be in the path of the shadow.

The easiest technique is to make a pinhole projector. Take a piece of cardboard with a small (1 millimeter) hole punched in it, and hold it several feet above a light surface, such as a concrete sidewalk or a white sheet of paper, so that the hole is "aimed" at the Sun. The hole produces a fuzzy but adequate image of the eclipsed Sun. Alternatively, if it's the right time of year, you can let the tiny spaces between a tree's leaves form multiple pinhole images against a wall or sidewalk. Watching hundreds of little crescent Suns dancing in the breeze can be captivating. A kitchen colander also makes an excellent pinhole projector.

Although there are safe filters for looking at the Sun directly, people have suffered eye damage by looking through improper filters, or no filter at all. For example, neutral density photographic filters are not safe because they transmit infrared radiation that can cause severe damage to the retina. Also unsafe are smoked glass, completely exposed color film, sunglasses, and many other homemade filters. Safe filters include welders' goggles and specially designed eclipse glasses.

You should certainly look at the Sun directly when it is totally eclipsed, even through binoculars or telescopes. Unfortunately, the total phase, as we discussed, is all too brief. But if you know when it is coming and going, be sure you look, for it's an unforgettably beautiful sight. And, despite the ancient folklore that presents eclipses as dangerous times to be outdoors, the partial phases of eclipses—as long as you are not looking directly at the Sun—are not any more dangerous than being out in sunlight.

During past eclipses, unnecessary panic has been created by uninformed public officials acting with the best intentions. There were two marvelous total eclipses in Australia in the twentieth century during which townspeople held newspapers over their heads for protection and schoolchildren cowered indoors with their heads under their desks. What a pity that all those people missed what would have been one of the most memorable experiences of their lifetimes.

On August 21, 2017, a total eclipse of the Sun was visible across a large swath of the continental United States, and was seen by millions of people from around the country and the world (a).



Figure 4.25 : 2017 Total Solar and Lunar Eclipse (a) The eclipsed Sun August 21, 2017, showing remarkable detail in the Sun's outer atmosphere. This is a composite of short, medium, and long exposures, as no single exposure can capture the huge range of brightness the Sun exhibits. (b) A total eclipse of the Moon seen over California on January 31, 2018. The Moon moves slowly into the Earth's shadow, looks red when the eclipse is total and red sunlight refracts through the Earth's atmosphere, and then slowly moves out of the shadow. (credit a: modification of work by Rick Fienberg, American Astronomical Socity/TravelQuest International; credit b: modification of work by Brian Day.)

Link to Learning

For the August 2017 eclipse, the United States postal service issued a special commemorative stamp — the first ever with "thermochromic ink" which changes when you touch it.

Footnotes

- 2Eclipse glasses are available in many planetarium and observatory gift stores, and also from the two main U.S. manufacturers: American Paper Optics and Rainbow Symphony.

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2.9: Key Terms

apparent solar time
time as measured by the position of the Sun in the sky (the time that would be indicated by a sundial)

declination
the angular distance north or south of the celestial equator

great circle
a circle on the surface of a sphere that is the curve of intersection of the sphere with a plane passing through its center

International Date Line
an arbitrary line on the surface of Earth near longitude 180° across which the date changes by one day

lunar eclipse
an eclipse of the Moon, in which the Moon moves into the shadow of Earth; lunar eclipses can occur only at the time of full moon

mean solar time
time based on the rotation of Earth; mean solar time passes at a constant rate, unlike apparent solar time

meridian
a great circle on the terrestrial or celestial sphere that passes through the poles

phases of the Moon
the different appearance of light and dark on the Moon as seen from Earth during its monthly cycle, from new moon to full moon and back to new moon

right ascension
the coordinate for measuring the east-west positions of celestial bodies; the angle measured eastward along the celestial equator from the vernal equinox to the hour circle passing through a body

sidereal day
Earth’s rotation period as defined by the positions of the stars in the sky; the time between successive passages of the same star through the meridian

sidereal month
the period of the Moon’s revolution about Earth measured with respect to the stars

solar day
Earth’s rotation period as defined by the position of the Sun in the sky; the time between successive passages of the Sun through the meridian

solar eclipse
an eclipse of the Sun by the Moon, caused by the passage of the Moon in front of the Sun; solar eclipses can occur only at the time of the new moon

solar month
the time interval in which the phases repeat—say, from full to full phase

synchronous rotation
when a body (for example, the Moon) rotates at the same rate that it revolves around another body

tides

alternate rising and falling of sea level caused by the difference in the strength of the Moon’s gravitational pull on different parts of Earth

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2.10: Summary

4.1 Earth and Sky

The terrestrial system of latitude and longitude makes use of the great circles called meridians. Longitude is arbitrarily set to 0° at the Royal Observatory at Greenwich, England. An analogous celestial coordinate system is called right ascension (RA) and declination, with 0° of declination starting at the vernal equinox. These coordinate systems help us locate any object on the celestial sphere. The Foucault pendulum is a way to demonstrate that Earth is turning.

4.2 The Seasons

The familiar cycle of the seasons results from the 23.5° tilt of Earth's axis of rotation. At the summer solstice, the Sun is higher in the sky and its rays strike Earth more directly. The Sun is in the sky for more than half of the day and can heat Earth longer. At the winter solstice, the Sun is low in the sky and its rays come in at more of an angle; in addition, it is up for fewer than 12 hours, so those rays have less time to heat. At the vernal and autumnal equinoxes, the Sun is on the celestial equator and we get about 12 hours of day and night. The seasons are different at different latitudes.

4.3 Keeping Time

The basic unit of astronomical time is the day—either the solar day (reckoned by the Sun) or the sidereal day (reckoned by the stars). Apparent solar time is based on the position of the Sun in the sky, and mean solar time is based on the average value of a solar day during the year. By international agreement, we define 24 time zones around the world, each with its own standard time. The convention of the International Date Line is necessary to reconcile times on different parts of Earth.

4.4 The Calendar

The fundamental problem of the calendar is to reconcile the incommensurable lengths of the day, month, and year. Most modern calendars, beginning with the Roman (Julian) calendar of the first century BCE, neglect the problem of the month and concentrate on achieving the correct number of days in a year by using such conventions as the leap year. Today, most of the world has adopted the Gregorian calendar established in 1582 while finding ways to coexist with the older lunar calendars' system of months.

4.5 Phases and Motions of the Moon

The Moon's monthly cycle of phases results from the changing angle of its illumination by the Sun. The full moon is visible in the sky only during the night; other phases are visible during the day as well. Because its period of revolution is the same as its period of rotation, the Moon always keeps the same face toward Earth.

4.6 Ocean Tides and the Moon

The twice-daily ocean tides are primarily the result of the Moon's differential force on the material of Earth's crust and ocean. These tidal forces cause ocean water to flow into two tidal bulges on opposite sides of Earth; each day, Earth rotates through these bulges. Actual ocean tides are complicated by the additional effects of the Sun and by the shape of the coasts and ocean basins.

4.7 Eclipses of the Sun and Moon

The Sun and Moon have nearly the same angular size (about 1/2°). A solar eclipse occurs when the Moon moves between the Sun and Earth, casting its shadow on a part of Earth's surface. If the eclipse is total, the light from the bright disk of the Sun is completely blocked, and the solar atmosphere (the corona) comes into view. Solar eclipses take place rarely in any one location, but they are among the most spectacular sights in nature. A lunar eclipse takes place when the Moon moves into Earth's shadow; it is visible (weather permitting) from the entire night hemisphere of Earth.

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2.11: For Further Exploration

Articles

Bakich, M. “Your Twenty-Year Solar Eclipse Planner.” *Astronomy* (October 2008): 74. Describes the circumstances of upcoming total eclipses of the Sun.

Coco, M. “Not Just Another Pretty Phase.” *Astronomy* (July 1994): 76. Moon phases explained.

Espenak, F., & Anderson, J. “Get Ready for America’s Coast to Coast Experience.” *Sky & Telescope* (February 2016): 22.

Gingerich, O. “Notes on the Gregorian Calendar Reform.” *Sky & Telescope* (December 1982): 530.

Kluepfel, C. “How Accurate Is the Gregorian Calendar?” *Sky & Telescope* (November 1982): 417.

Krupp, E. “Calendar Worlds.” *Sky & Telescope* (January 2001): 103. On how the days of the week got their names.

Krupp, E. “Behind the Curve.” *Sky & Telescope* (September 2002): 68. On the reform of the calendar by Pope Gregory XIII.

MacRobert, A., & Sinnott, R. “Young Moon Hunting.” *Sky & Telescope* (February 2005): 75. Hints for finding the Moon as soon after its new phase as possible.

Pasachoff, J. “Solar Eclipse Science: Still Going Strong.” *Sky & Telescope* (February 2001): 40. On what we have learned and are still learning from eclipses.

Regas, D. “The Quest for Totality.” *Sky & Telescope* (July 2012): 36. On eclipse chasing as a hobby.

Schaefer, B. “Lunar Eclipses That Changed the World.” *Sky & Telescope* (December 1992): 639.

Schaefer, B. “Solar Eclipses That Changed the World.” *Sky & Telescope* (May 1994): 36.

Websites

Ancient Observatories, Timeless Knowledge (Stanford Solar Center): http://solar-center.stanford.edu/AO/. An introduction to ancient sites where the movements of celestial objects were tracked over the years (with a special focus on tracking the Sun).

Astronomical Data Services: https://www.usno.navy.mil/USNO/astronomical-applications/data-services. This rich site from the U.S. Naval Observatory has information about Earth, the Moon, and the sky, with tables and online calculators.

Calendars through the Ages: http://www.webexhibits.org/calendars/index.html. Like a good museum exhibit on the Web.

Calendar Zone: http://www.calendarzone.com/. Everything you wanted to ask or know about calendars and timekeeping, with links from around the world.

Eclipse Maps: http://www.eclipse-maps.com/Eclipse-Maps/Welcome.html. Michael Zeiler specializes in presenting helpful and interactive maps of where solar eclipses will be visible

Eclipse Predictions: EclipseWise: http://www.eclipsewise.com/intro.html. An introductory site on future eclipses and eclipse observing by NASA’s Fred Espenak.

History of the International Date Line: http://www.staff.science.uu.nl/~gent0113/idl/idl.htm. From R. H. van Gent at Utrecht University in the Netherlands.

Lunacy and the Full Moon: www.scientificamerican.com/article/lunacy-and-the-full-moon/. This *Scientific American* article explores whether the Moon’s phase is related to strange behavior.

Moon Phase Calculator: https://stardate.org/nightsky/moon. Keep track of the phases of the Moon with this calendar.

NASA Eclipse Website: http://eclipse.gsfc.nasa.gov/eclipse.html. This site, by NASA’s eclipse expert Fred Espenak, contains a wealth of information on lunar and solar eclipses, past and future, as well as observing and photography links.

Phases of the Moon Gallery and Information: http://astropixels.com/moon/phases/phasesgallery.html. Photographs and descriptions presented by NASA’s Fred Espenak.

Time and Date Website: http://www.timeanddate.com/. Comprehensive resource about how we keep time on Earth; has time zone converters and many other historical and mathematical tools.

Walk through Time: The Evolution of Time Measurement through the Ages (National Institute of Standards and Technology): http://www.nist.gov/pml/general/time/.

Videos

Bill Nye, the Science Guy, Explains the Seasons: https://www.youtube.com/watch?v=KUU7IyfR34o. For kids, but college students can enjoy the bad jokes, too (4:45).

Geography Lesson Idea: Time Zones: https://www.youtube.com/watch?v=-j-SWKtWEcU. (3:11).

How to View a Solar Eclipse: www.exploratorium.edu/eclipse/how-to-view-eclipse. (1:35).

Shadow of the Moon: https://www.youtube.com/watch?v=XNcfKUJwnjM. This NASA video explains eclipses of the Sun, with discussion and animation, focusing on a 2015 eclipse, and shows what an eclipse looks like from space (1:54).

Strangest Time Zones in the World: https://www.youtube.com/watch?v=uW6QqcmCfm8. (8:38).

Understanding Lunar Eclipses: https://www.youtube.com/watch?v=lNi5UFpales. This NASA video explains why there isn't an eclipse every month, with good animation (1:58).

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2.12: Collaborative Group Activities

A. Have your group brainstorm about other ways (besides the Foucault pendulum) you could prove that it is our Earth that is turning once a day, and not the sky turning around us. (Hint: How does the spinning of Earth affect the oceans and the atmosphere?)

B. What would the seasons on Earth be like if Earth's axis were not tilted? Discuss with your group how many things about life on Earth you think would be different.

C. After college and graduate training, members of your U.S. student group are asked to set up a school in New Zealand. Describe some ways your yearly school schedule in the Southern Hemisphere would differ from what students are used to in the Northern Hemisphere.

D. During the traditional U.S. Christmas vacation weeks, you are sent to the vicinity of the South Pole on a research expedition (depending on how well you did on your astronomy midterm, either as a research assistant or as a short-order cook!). Have your group discuss how the days and nights will be different there and how these differences might affect you during your stay.

E. Discuss with your group all the stories you have heard about the full moon and crazy behavior. Why do members of your group think people associate crazy behavior with the full moon? What other legends besides vampire stories are connected with the phases of the Moon? (Hint: Think Professor Lupin in the Harry Potter stories, for example.)

F. Your college town becomes the founding site for a strange new cult that worships the Moon. These true believers gather regularly around sunset and do a dance in which they must extend their arms in the direction of the Moon. Have your group discuss which way their arms will be pointing at sunset when the Moon is new, first quarter, full, and third quarter.

G. Changes of the seasons play a large part in our yearly plans and concerns. The seasons have inspired music, stories, poetry, art, and much groaning from students during snowstorms. Search online to come up with some examples of the seasons being celebrated or overcome in fields other than science.

H. Use the information in Appendix H and online to figure out when the next eclipse of the Sun or eclipse of the Moon will be visible from where your group is going to college or from where your group members live. What time of day will the eclipse be visible? Will it be a total or partial eclipse? What preparations can you make to have an enjoyable and safe eclipse experience? How do these preparations differ between a solar and lunar eclipse?

I. On Mars, a day (often called a sol) is 24 hours and 40 minutes. Since Mars takes longer to go around the Sun, a year is 668.6 sols. Mars has two tiny moons, Phobos and Deimos. Phobos, the inner moon, rises in the west and sets in the east, taking 11 hours from moonrise to the next moonrise. Using your calculators and imaginations, have your group members come up with a calendar for Mars. (After you do your own, and only after, you can search online for the many suggestions that have been made for a martian calendar over the years.)

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CHAPTER OVERVIEW

2.13: Exercises

2.13.1: Review Questions

2.13.2: Thought Questions

2.13.3: Figuring for Yourself

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2.13.1: Review Questions

Review Questions

1.

Discuss how latitude and longitude on Earth are similar to declination and right ascension in the sky.

2.

What is the latitude of the North Pole? The South Pole? Why does longitude have no meaning at the North and South Poles?

3.

Make a list of each main phase of the Moon, describing roughly when the Moon rises and sets for each phase. During which phase can you see the Moon in the middle of the morning? In the middle of the afternoon?

4.

What are advantages and disadvantages of apparent solar time? How is the situation improved by introducing mean solar time and standard time?

5.

What are the two ways that the tilt of Earth's axis causes the summers in the United States to be warmer than the winters?

6.

Why is it difficult to construct a practical calendar based on the Moon's cycle of phases?

7.

Explain why there are two high tides and two low tides each day. Strictly speaking, should the period during which there are two high tides be 24 hours? If not, what should the interval be?

8.

What is the phase of the Moon during a total solar eclipse? During a total lunar eclipse?

9.

On a globe or world map, find the nearest marked latitude line to your location. Is this an example of a great circle? Explain.

10.

Explain three lines of evidence that indicate that the seasons in North America are not caused by the changing Earth-Sun distance as a result of Earth's elliptical orbit around the Sun.

11.

What is the origin of the terms "a.m." and "p.m." in our timekeeping?

12.

Explain the origin of the leap year. Why is it necessary?

13.

Explain why the year 1800 was not a leap year, even though years divisible by four are normally considered to be leap years.

14.

What fraction of the Moon's visible face is illuminated during first quarter phase? Why is this phase called first quarter?

15.

Why don't lunar eclipses happen during every full moon?

16.

Why does the Moon create tidal bulges on both sides of Earth instead of only on the side of Earth closest to the Moon?

17.

Why do the heights of the tides change over the course of a month?

18.

Explain how tidal forces are causing Earth to slow down.

19.

Explain how tidal forces are causing the Moon to slowly recede from Earth.

20.

Explain why the Gregorian calendar modified the nature of the leap year from its original definition in the Julian calendar.

21.

The term *equinox* translates as “equal night.” Explain why this translation makes sense from an astronomical point of view.

22.

The term *solstice* translates as “Sun stop.” Explain why this translation makes sense from an astronomical point of view.

23.

Why is the warmest day of the year in the United States (or in the Northern Hemisphere temperate zone) usually in August rather than on the day of the summer solstice, in late June?

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2.13.2: Thought Questions

Thought Questions

24.

When Earth's Northern Hemisphere is tilted toward the Sun during June, some would argue that the cause of our seasons is that the Northern Hemisphere is physically closer to the Sun than the Southern Hemisphere, and this is the primary reason the Northern Hemisphere is warmer. What argument or line of evidence could contradict this idea?

25.

Where are you on Earth if you experience each of the following? (Refer to the discussion in Observing the Sky: The Birth of Astronomy as well as this chapter.)

A. The stars rise and set perpendicular to the horizon.
B. The stars circle the sky parallel to the horizon.
C. The celestial equator passes through the zenith.
D. In the course of a year, all stars are visible.
E. The Sun rises on March 21 and does not set until September 21 (ideally).

26.

In countries at far northern latitudes, the winter months tend to be so cloudy that astronomical observations are nearly impossible. Why can't good observations of the stars be made at those places during the summer months?

27.

What is the phase of the Moon if it . . .

A. rises at 3:00 p.m.?
B. is highest in the sky at sunrise?
C. sets at 10:00 a.m.?

28.

A car accident occurs around midnight on the night of a full moon. The driver at fault claims he was blinded momentarily by the Moon rising on the eastern horizon. Should the police believe him?

29.

The secret recipe to the ever-popular veggie burgers in the college cafeteria is hidden in a drawer in the director's office. Two students decide to break in to get their hands on it, but they want to do it a few hours before dawn on a night when there is no Moon, so they are less likely to be caught. What phases of the Moon would suit their plans?

30.

Your great-great-grandfather, who often exaggerated events in his own life, once told your relatives about a terrific adventure he had on February 29, 1900. Why would this story make you suspicious?

31.

One year in the future, when money is no object, you enjoy your birthday so much that you want to have another one right away. You get into your supersonic jet. Where should you and the people celebrating with you travel? From what direction should you approach? Explain.

32.

Suppose you lived in the crater Copernicus on the side of the Moon facing Earth.

A. How often would the Sun rise?
B. How often would Earth set?
C. During what fraction of the time would you be able to see the stars?

33.

In a lunar eclipse, does the Moon enter the shadow of Earth from the east or west side? Explain.

34.

Describe what an observer at the crater Copernicus would see while the Moon is eclipsed on Earth. What would the same observer see during what would be a total solar eclipse as viewed from Earth?

35.

The day on Mars is 1.026 Earth-days long. The martian year lasts 686.98 Earth-days. The two moons of Mars take 0.32 Earth-day (for Phobos) and 1.26 Earth-days (for Deimos) to circle the planet. You are given the task of coming up with a martian calendar for a new Mars colony. Would a solar or lunar calendar be better for tracking the seasons?

36.

What is the right ascension and declination of the vernal equinox?

37.

What is the right ascension and declination of the autumnal equinox?

38.

What is the right ascension and declination of the Sun at noon on the summer solstice in the Northern Hemisphere?

39.

During summer in the Northern Hemisphere, the North Pole is illuminated by the Sun 24 hours per day. During this time, the temperature often does not rise above the freezing point of water. Explain why.

40.

On the day of the vernal equinox, the day length for all places on Earth is actually slightly longer than 12 hours. Explain why.

41.

Regions north of the Arctic Circle are known as the “land of the midnight Sun.” Explain what this means from an astronomical perspective.

42.

In a part of Earth’s orbit where Earth is moving faster than usual around the Sun, would the length of the sidereal day change? If so, how? Explain.

43.

In a part of Earth’s orbit where Earth is moving faster than usual around the Sun, would the length of the solar day change? If so, how? Explain.

44.

If Sirius rises at 8:00 p.m. tonight, at what time will it rise tomorrow night, to the nearest minute? Explain.

45.

What are three lines of evidence you could use to indicate that the phases of the Moon are not caused by the shadow of Earth falling on the Moon?

46.

If the Moon rises at a given location at 6:00 p.m. today, about what time will it rise tomorrow night?

47.

Explain why some solar eclipses are total and some are annular.

48.

Why do lunar eclipses typically last much longer than solar eclipses?

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2.13.3: Figuring for Yourself

Figuring for Yourself

49.

Suppose Earth took exactly 300.0 days to go around the Sun, and everything else (the day, the month) was the same. What kind of calendar would we have? How would this affect the seasons?

50.

Consider a calendar based entirely on the day and the month (the Moon’s period from full phase to full phase). How many days are there in a month? Can you figure out a scheme analogous to leap year to make this calendar work?

51.

If a star rises at 8:30 p.m. tonight, approximately what time will it rise two months from now?

52.

What is the altitude of the Sun at noon on December 22, as seen from a place on the Tropic of Cancer?

53.

Show that the Gregorian calendar will be in error by 1 day in about 3300 years.

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CHAPTER OVERVIEW

3: Observing the Sky - The Birth of Astronomy

Much to your surprise, a member of the Flat Earth Society moves in next door. He believes that Earth is flat and all the NASA images of a spherical Earth are either faked or simply show the round (but flat) disk of Earth from above. How could you prove to your new neighbor that Earth really is a sphere? (When you've thought about this on your own, you can check later in the chapter for some suggested answers.)

Today, few people really spend much time looking at the night sky. In ancient days, before electric lights robbed so many people of the beauty of the sky, the stars and planets were an important aspect of everyone's daily life. All the records that we have—on paper and in stone—show that ancient civilizations around the world noticed, worshipped, and tried to understand the lights in the sky and fit them into their own view of the world. These ancient observers found both majestic regularity and never-ending surprise in the motions of the heavens. Through their careful study of the planets, the Greeks and later the Romans laid the foundation of the science of astronomy.

3.1: Thinking Ahead
3.2: The Sky Above
3.3: Ancient Astronomy
3.4: Astrology and Astronomy
3.5: The Birth of Modern Astronomy
3.6: Key Terms
3.7: Summary
3.8: For Further Exploration
3.9: Collaborative Group Activities
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3.10.2: Thought Questions
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3.1: Thinking Ahead



Figure 2.1 : Night Sky. In this panoramic photograph of the night sky from the Atacama Desert in Chile, we can see the central portion of the Milky Way Galaxy arcing upward in the center of the frame. On the left, the Large Magellanic Cloud and the Small Magellanic Cloud (smaller galaxies that orbit the Milky Way Galaxy) are easily visible from the Southern Hemisphere. (credit: modification of work by ESO/Y. Beletsky)

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3.2: The Sky Above

Learning Objectives

By the end of this section, you will be able to:

- Define the main features of the celestial sphere
- Explain the system astronomers use to describe the sky
- Describe how motions of the stars appear to us on Earth
- Describe how motions of the Sun, Moon, and planets appear to us on Earth
- Understand the modern meaning of the term *constellation*

Our senses suggest to us that Earth is the center of the universe—the hub around which the heavens turn. This geocentric (Earth-centered) view was what almost everyone believed until the European Renaissance. After all, it is simple, logical, and seemingly self-evident. Furthermore, the geocentric perspective reinforced those philosophical and religious systems that taught the unique role of human beings as the central focus of the cosmos. However, the geocentric view happens to be wrong. One of the great themes of our intellectual history is the overthrow of the geocentric perspective. Let us, therefore, take a look at the steps by which we reevaluated the place of our world in the cosmic order.

The Celestial Sphere

If you go on a camping trip or live far from city lights, your view of the sky on a clear night is pretty much identical to that seen by people all over the world before the invention of the telescope. Gazing up, you get the impression that the sky is a great hollow dome with you at the center (Figure 2.2), and all the stars are an equal distance from you on the surface of the dome. The top of that dome, the point directly above your head, is called the zenith, and where the dome meets Earth is called the horizon. From the sea or a flat prairie, it is easy to see the horizon as a circle around you, but from most places where people live today, the horizon is at least partially hidden by mountains, trees, buildings, or smog.

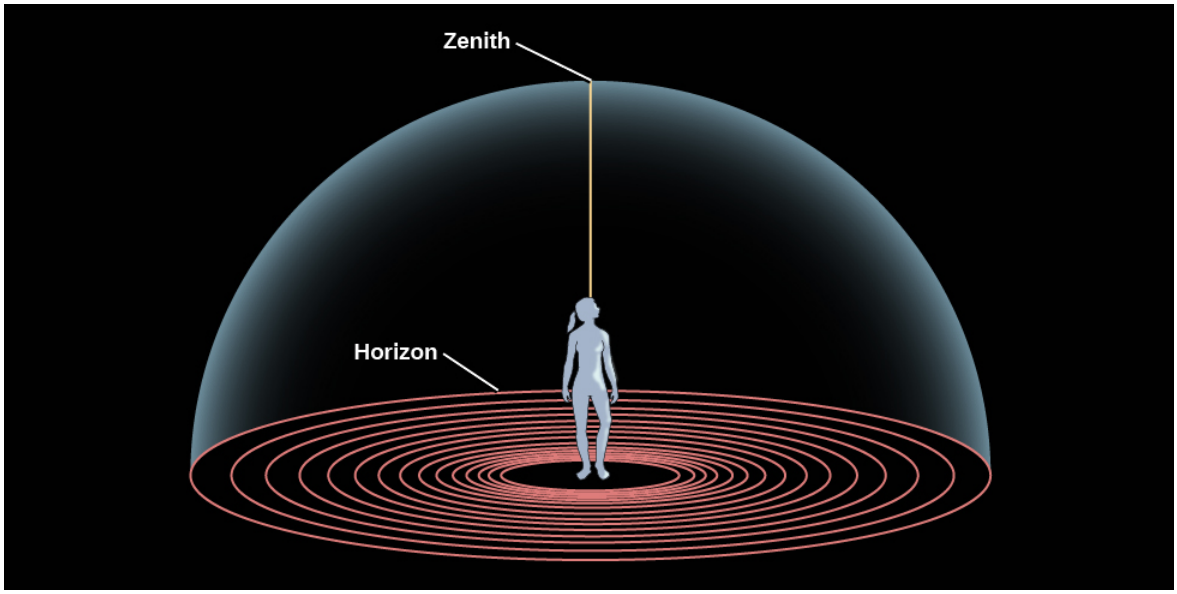


Figure 2.2 : The Sky around Us. The horizon is where the sky meets the ground; an observer's zenith is the point directly overhead.

If you lie back in an open field and observe the night sky for hours, as ancient shepherds and travelers regularly did, you will see stars rising on the eastern horizon (just as the Sun and Moon do), moving across the dome of the sky in the course of the night, and setting on the western horizon. Watching the sky turn like this night after night, you might eventually get the idea that the dome of the sky is really part of a great sphere that is turning around you, bringing different stars into view as it turns. The early Greeks regarded the sky as just such a celestial sphere (Figure 2.3). Some thought of it as an actual sphere of transparent crystalline material, with the stars embedded in it like tiny jewels.

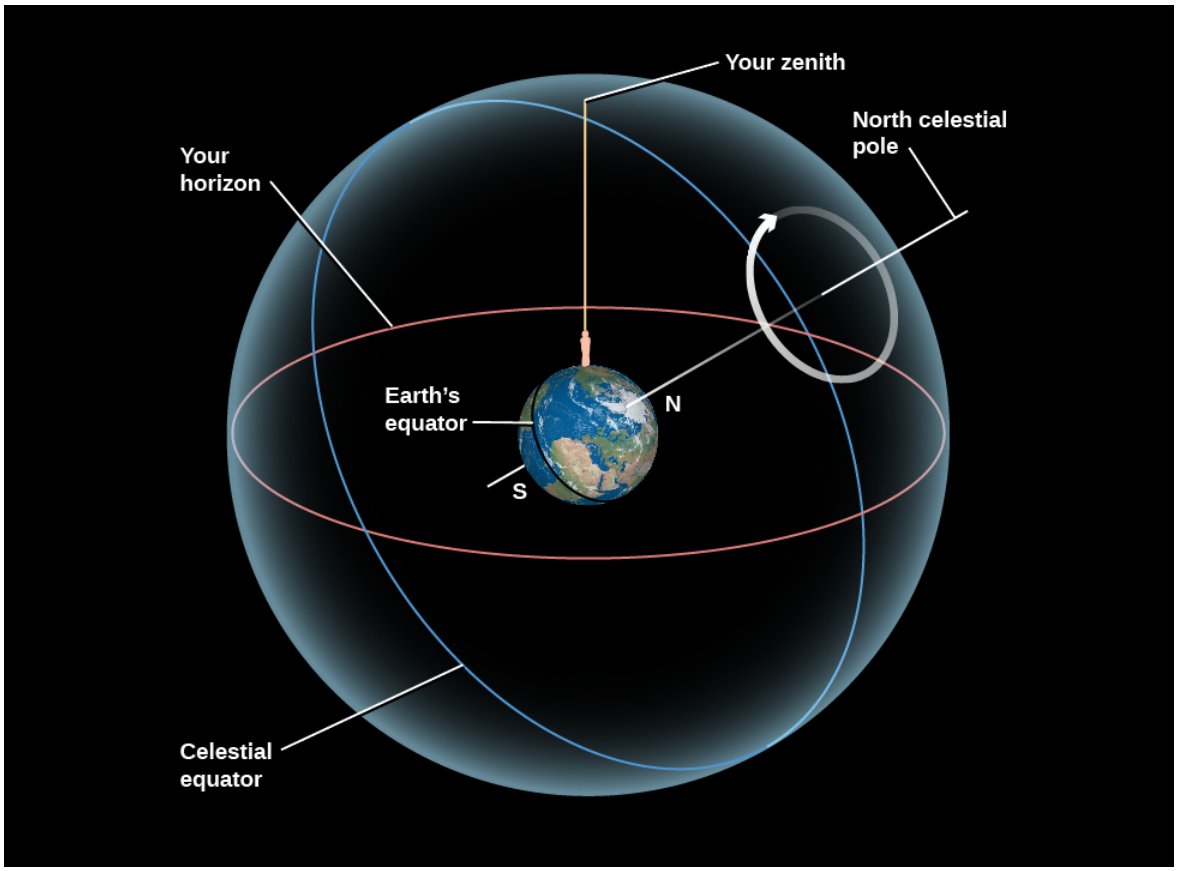


Figure 2.3 : Circles on the Celestial Sphere. Here we show the (imaginary) celestial sphere around Earth, on which objects are fixed, and which rotates around Earth on an axis. In reality, it is Earth that turns around this axis, creating the illusion that the sky revolves around us. Note that Earth in this picture has been tilted so that your location is at the top and the North Pole is where the N is. The apparent motion of celestial objects in the sky around the pole is shown by the circular arrow.

Today, we know that it is not the celestial sphere that turns as night and day proceed, but rather the planet on which we live. We can put an imaginary stick through Earth's North and South Poles, representing our planet's axis. It is because Earth turns on this axis every 24 hours that we see the Sun, Moon, and stars rise and set with clockwork regularity. Today, we know that these celestial objects are not really on a dome, but at greatly varying distances from us in space. Nevertheless, it is sometimes still convenient to talk about the celestial dome or sphere to help us keep track of objects in the sky. There is even a special theater, called a *planetarium*, in which we project a simulation of the stars and planets onto a white dome.

As the celestial sphere rotates, the objects on it maintain their positions with respect to one another. A grouping of stars such as the Big Dipper has the same shape during the course of the night, although it turns with the sky. During a single night, even objects we know to have significant motions of their own, such as the nearby planets, seem fixed relative to the stars. Only meteors—brief "shooting stars" that flash into view for just a few seconds—move appreciably with respect to other objects on the celestial sphere. (This is because they are not stars at all. Rather, they are small pieces of cosmic dust, burning up as they hit Earth's atmosphere.) We can use the fact that the entire celestial sphere seems to turn together to help us set up systems for keeping track of what things are visible in the sky and where they happen to be at a given time.

Celestial Poles and Celestial Equator

To help orient us in the turning sky, astronomers use a system that extends Earth's axis points into the sky. Imagine a line going through Earth, connecting the North and South Poles. This is Earth's axis, and Earth rotates about this line. If we extend this imaginary line outward from Earth, the points where this line intersects the celestial sphere are called the *north celestial pole* and the *south celestial pole*. As Earth rotates about its axis, the sky appears to turn in the opposite direction around those celestial poles

(Figure 2.4). We also (in our imagination) throw Earth's equator onto the sky and call this the celestial equator. It lies halfway between the celestial poles, just as Earth's equator lies halfway between our planet's poles.



Figure 2.4 : Circling the South Celestial Pole. This long-exposure photo shows trails left by stars as a result of the apparent rotation of the celestial sphere around the south celestial pole. (In reality, it is Earth that rotates.) (Credit: ESO/Iztok Bončina)

Now let's imagine how riding on different parts of our spinning Earth affects our view of the sky. The apparent motion of the celestial sphere depends on your latitude (position north or south of the equator). First of all, notice that Earth's axis is pointing at the celestial poles, so these two points in the sky do not appear to turn.

If you stood at the North Pole of Earth, for example, you would see the north celestial pole overhead, at your zenith. The celestial equator, 90° from the celestial poles, would lie along your horizon. As you watched the stars during the course of the night, they would all circle around the celestial pole, with none rising or setting. Only that half of the sky north of the celestial equator is ever visible to an observer at the North Pole. Similarly, an observer at the South Pole would see only the southern half of the sky.

If you were at Earth's equator, on the other hand, you see the celestial equator (which, after all, is just an "extension" of Earth's equator) pass overhead through your zenith. The celestial poles, being 90° from the celestial equator, must then be at the north and south points on your horizon. As the sky turns, all stars rise and set; they move straight up from the east side of the horizon and set straight down on the west side. During a 24-hour period, all stars are above the horizon exactly half the time. (Of course, during some of those hours, the Sun is too bright for us to see them.)

What would an observer in the latitudes of the United States or Europe see? Remember, we are neither at Earth's pole nor at the equator, but in between them. For those in the continental United States and Europe, the north celestial pole is neither overhead nor on the horizon, but in between. It appears above the northern horizon at an angular height, or altitude, equal to the observer's latitude. In San Francisco, for example, where the latitude is 38° N, the north celestial pole is 38° above the northern horizon.

For an observer at 38° N latitude, the south celestial pole is 38° below the southern horizon and, thus, never visible. As Earth turns, the whole sky seems to pivot about the north celestial pole. For this observer, stars within 38° of the North Pole can never set. They are always above the horizon, day and night. This part of the sky is called the north circumpolar zone. For observers in the continental United States, the Big Dipper, Little Dipper, and Cassiopeia are examples of star groups in the north circumpolar zone. On the other hand, stars within 38° of the south celestial pole never rise. That part of the sky is the south circumpolar zone. To most U.S. observers, the Southern Cross is in that zone. (Don't worry if you are not familiar with the star groups just mentioned; we will introduce them more formally later on.)

At this particular time in Earth's history, there happens to be a star very close to the north celestial pole. It is called Polaris, the pole star, and has the distinction of being the star that moves the least amount as the northern sky turns each day. Because it moved so little while the other stars moved much more, it played a special role in the mythology of several Native American tribes, for example (some called it the "fastener of the sky").

Astronomy Basics: What's Your Angle?

Astronomers measure how far apart objects appear in the sky by using angles. By definition, there are 360° in a circle, so a circle stretching completely around the celestial sphere contains 360°. The half-sphere or dome of the sky then contains 180° from horizon to opposite horizon. Thus, if two stars are 18° apart, their separation spans about 1/10 of the dome of the sky. To give you a sense of how big a degree is, the full Moon is about half a degree across. This is about the width of your smallest finger (pinkie) seen at arm's length.

Rising and Setting of the Sun

We described the movement of stars in the night sky, but what about during the daytime? The stars continue to circle during the day, but the brilliance of the Sun makes them difficult to see. (The Moon can often be seen in the daylight, however.) On any given day, we can think of the Sun as being located at some position on the hypothetical celestial sphere. When the Sun rises—that is, when the rotation of Earth carries the Sun above the horizon—sunlight is scattered by the molecules of our atmosphere, filling our sky with light and hiding the stars above the horizon.

For thousands of years, astronomers have been aware that the Sun does more than just rise and set. It changes position gradually on the celestial sphere, moving each day about 1° to the east relative to the stars. Very reasonably, the ancients thought this meant the Sun was slowly moving around Earth, taking a period of time we call 1 year to make a full circle. Today, of course, we know it is Earth that is going around the Sun, but the effect is the same: the Sun's position in our sky changes day to day. We have a similar experience when we walk around a campfire at night; we see the flames appear in front of each person seated about the fire in turn.

The path the Sun appears to take around the celestial sphere each year is called the ecliptic (Figure 2.6). Because of its motion on the ecliptic, the Sun rises about 4 minutes later each day with respect to the stars. Earth must make just a bit more than one complete rotation (with respect to the stars) to bring the Sun up again.

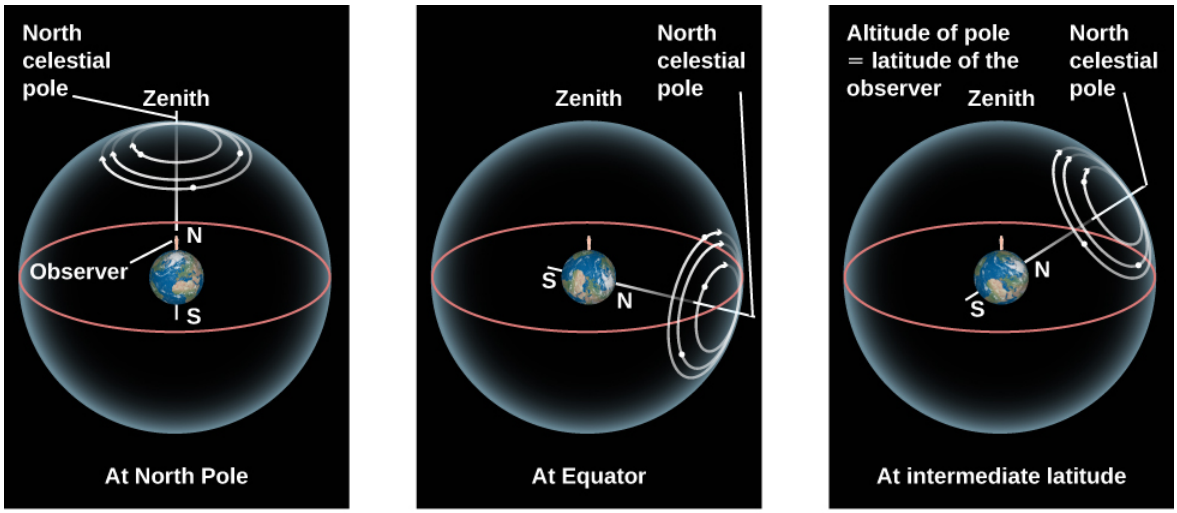


Figure 2.5 : Star Circles at Different Latitudes. The turning of the sky looks different depending on your latitude on Earth. The red circle in each case is your horizon. Your zenith is the point above your head. (a) At the North Pole, the stars circle the zenith and do not rise and set. (b) At the equator, the celestial poles are on the horizon, and the stars rise straight up and set straight down. (c) At intermediate latitudes, the north celestial pole is at some position between overhead and the horizon. Its angle above the horizon turns out to be equal to the observer's latitude. Stars rise and set at an angle to the horizon.

As the months go by and we look at the Sun from different places in our orbit, we see it projected against different places in our orbit, and thus against different stars in the background (Figure 2.6 and Table 2.1)—or we would, at least, if we could see the stars in the daytime. In practice, we must deduce which stars lie behind and beyond the Sun by observing the stars visible in the opposite direction at night. After a year, when Earth has completed one trip around the Sun, the Sun will appear to have completed one circuit of the sky along the ecliptic.

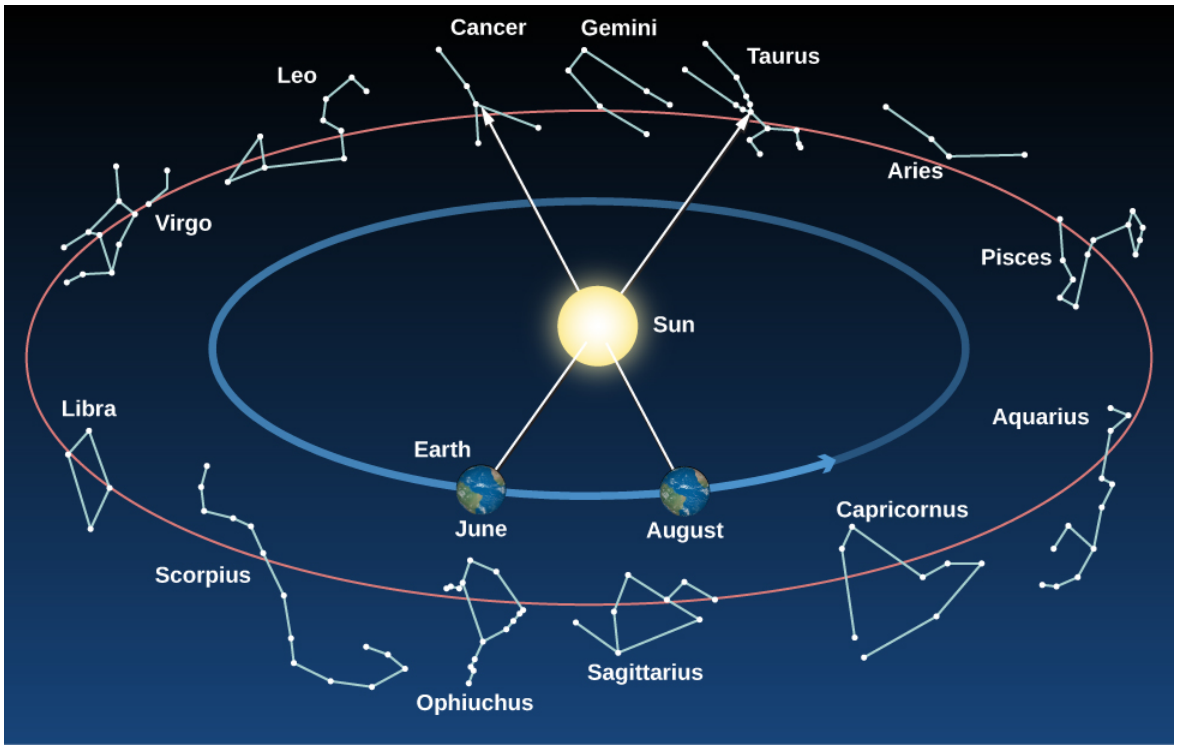


Figure 2.6 : Constellations on the Ecliptic. As Earth revolves around the Sun, we sit on “platform Earth” and see the Sun moving around the sky. The circle in the sky that the Sun appears to make around us in the course of a year is called the *ecliptic*. This circle (like all circles in the sky) goes through a set of constellations. The ancients thought these constellations, which the Sun (and the Moon and planets) visited, must be special and incorporated them into their system of astrology. Note that at any given time of the year, some of the constellations crossed by the ecliptic are visible in the night sky; others are in the day sky and are thus hidden by the brilliance of the Sun. (The term constellation will be defined more precisely in the next subsection.)

Table 2.1: Constellations on the Ecliptic

Constellation on the Ecliptic	Dates When the Sun Crosses It
Capricornus	January 21–February 16
Aquarius	February 16–March 11
Pisces	March 11–April 18
Aries	April 18–May 13
Taurus	May 13–June 22
Gemini	June 22–July 21
Cancer	July 21–August 10
Leo	August 10–September 16
Virgo	September 16–October 31
Libra	October 31–November 23
Scorpius	November 23–November 29
Ophiuchus	November 29–December 18
Sagittarius	December 18–January 21

The ecliptic does not lie along the celestial equator but is inclined to it at an angle of about 23.5°. In other words, the Sun's annual path in the sky is not linked with Earth's equator. This is because our planet's axis of rotation is tilted by about 23.5° from a vertical line sticking out of the plane of the ecliptic (Figure 2.7). Being tilted from "straight up" is not at all unusual among celestial bodies; Uranus and Pluto are actually tilted so much that they orbit the Sun "on their side."

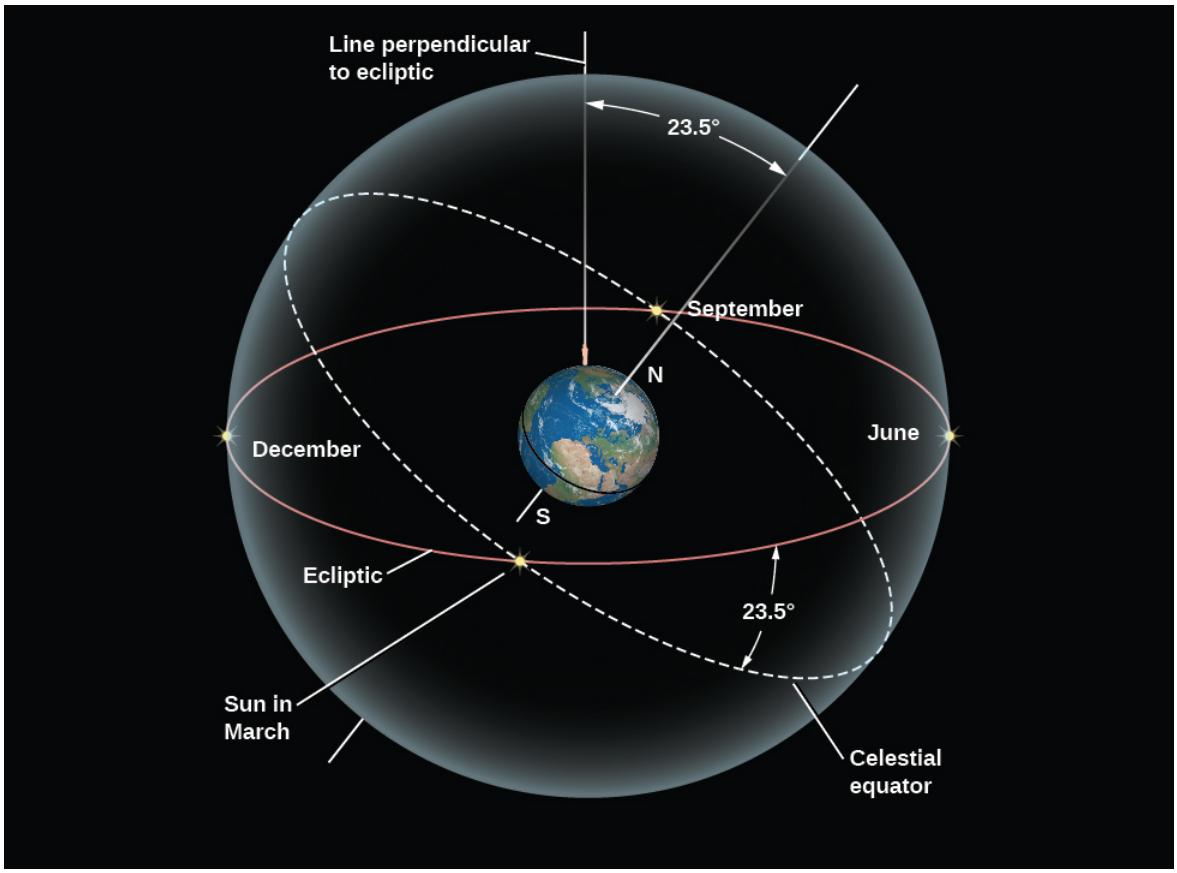


Figure 2.7 : The Celestial Tilt. The celestial equator is tilted by 23.5° to the ecliptic. As a result, North Americans and Europeans see the Sun north of the celestial equator and high in our sky in June, and south of the celestial equator and low in the sky in December.

The inclination of the ecliptic is the reason the Sun moves north and south in the sky as the seasons change. In Earth, Moon, and Sky, we discuss the progression of the seasons in more detail.

Fixed and Wandering Stars

The Sun is not the only object that moves among the fixed stars. The Moon and each of the planets that are visible to the unaided eye—Mercury, Venus, Mars, Jupiter, Saturn, and Uranus (although just barely)—also change their positions slowly from day to day. During a single day, the Moon and planets all rise and set as Earth turns, just as the Sun and stars do. But like the Sun, they have independent motions among the stars, superimposed on the daily rotation of the celestial sphere. Noticing these motions, the Greeks of 2000 years ago distinguished between what they called the *fixed stars*—those that maintain fixed patterns among themselves through many generations—and the *wandering stars*, or planets. The word "planet," in fact, means "wanderer" in ancient Greek.

Today, we do not regard the Sun and Moon as planets, but the ancients applied the term to all seven of the moving objects in the sky. Much of ancient astronomy was devoted to observing and predicting the motions of these celestial wanderers. They even dedicated a unit of time, the week, to the seven objects that move on their own; that's why there are 7 days in a week. The Moon, being Earth's nearest celestial neighbor, has the fastest apparent motion; it completes a trip around the sky in about 1 month (or *moonth*). To do this, the Moon moves about 12°, or 24 times its own apparent width on the sky, each day.

Example 2.1: Angles in the Sky

A circle consists of 360 degrees (°). When we measure the angle in the sky that something moves, we can use this formula:

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

This is true whether the motion is measured in kilometers per hour or degrees per hour; we just need to use consistent units.

As an example, let's say you notice the bright star Sirius due south from your observing location in the Northern Hemisphere. You note the time, and then later, you note the time that Sirius sets below the horizon. You find that Sirius has traveled an angular distance of about 75° in 5 h. About how many hours will it take for Sirius to return to its original location?

Solution

The speed of Sirius is $\frac{75^\circ}{5\text{ h}} = \frac{15^\circ}{1\text{ h}}$. If we want to know the time required for Sirius to return to its original location, we need to wait until it goes around a full circle, or 360°. Rearranging the formula for speed we were originally given, we find:

$$\text{time} = \frac{\text{distance}}{\text{speed}} = \frac{360^\circ}{15^\circ/\text{h}} = 24\text{ h}$$

The actual time is a few minutes shorter than this, and we will explore why in a later chapter.

Exercise 3.2.1

The Moon moves in the sky relative to the background stars (in addition to moving with the stars as a result of Earth's rotation.) Go outside at night and note the position of the Moon relative to nearby stars. Repeat the observation a few hours later. How far has the Moon moved? (For reference, the diameter of the Moon is about 0.5°.) Based on your estimate of its motion, how long will it take for the Moon to return to the position relative to the stars in which you first observed it?

Answer

The speed of the moon is 0.5°/1 h. To move a full 360°, the moon needs 720 h: $\frac{0.5^\circ}{1\text{ h}} = \frac{360^\circ}{720\text{ h}}$. Dividing 720 h by the conversion factor of 24 h/day reveals the lunar cycle is about 30 days.

The individual paths of the Moon and planets in the sky all lie close to the ecliptic, although not exactly on it. This is because the paths of the planets about the Sun, and of the Moon about Earth, are all in nearly the same plane, as if they were circles on a huge sheet of paper. The planets, the Sun, and the Moon are thus always found in the sky within a narrow 18-degree-wide belt, centered on the ecliptic, called the zodiac (Figure 2.6). (The root of the term "zodiac" is the same as that of the word "zoo" and means a collection of animals; many of the patterns of stars within the zodiac belt reminded the ancients of animals, such as a fish or a goat.)

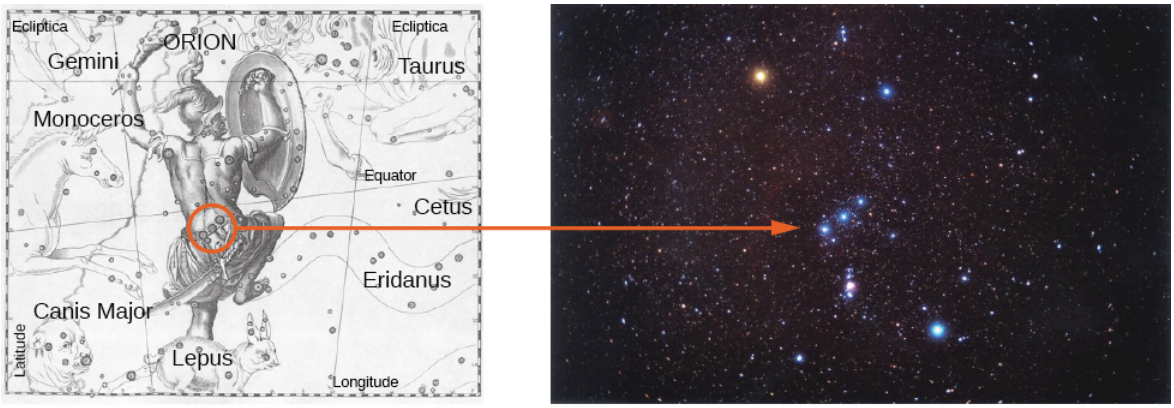
How the planets appear to move in the sky as the months pass is a combination of their actual motions plus the motion of Earth about the Sun; consequently, their paths are somewhat complex. As we will see, this complexity has fascinated and challenged astronomers for centuries.

Constellations

The backdrop for the motions of the "wanderers" in the sky is the canopy of stars. If there were no clouds in the sky and we were on a flat plain with nothing to obstruct our view, we could see about 3000 stars with the unaided eye. To find their way around such a multitude, the ancients found groupings of stars that made some familiar geometric pattern or (more rarely) resembled something they knew. Each civilization found its own patterns in the stars, much like a modern Rorschach test in which you are asked to discern patterns or pictures in a set of inkblots. The ancient Chinese, Egyptians, and Greeks, among others, found their own groupings—or constellations—of stars. These were helpful in navigating among the stars and in passing their star lore on to their children.

You may be familiar with some of the old star patterns we still use today, such as the Big Dipper, Little Dipper, and Orion the hunter, with his distinctive belt of three stars (Figure 2.8). However, many of the stars we see are not part of a distinctive star

pattern at all, and a telescope reveals millions of stars too faint for the eye to see. Therefore, during the early decades of the 20th century, astronomers from many countries decided to establish a more formal system for organizing the sky.



(a) (b)

Figure 2.8 : Orion. (a) The winter constellation of Orion, the hunter, is surrounded by neighboring constellations, as illustrated in the seventeenth-century atlas by Hevelius. (b) A photograph shows the Orion region in the sky. Note the three blue stars that make up the belt of the hunter. The bright red star above the belt denotes his armpit and is called Betelgeuse (pronounced “Beetel-juice”). The bright blue star below the belt is his foot and is called Rigel. (credit a: modification of work by Johannes Hevelius; b: modification of work by Matthew Spinelli)

Today, we use the term *constellation* to mean one of 88 sectors into which we divide the sky, much as the United States is divided into 50 states. The modern boundaries between the constellations are imaginary lines in the sky running north–south and east–west, so that each point in the sky falls in a specific constellation, although, like the states, not all constellations are the same size. All the constellations are listed in Appendix L. Whenever possible, we have named each modern constellation after the Latin translations of one of the ancient Greek star patterns that lies within it. Thus, the modern constellation of Orion is a kind of box on the sky, which includes, among many other objects, the stars that made up the ancient picture of the hunter. Some people use the term *asterism* to denote an especially noticeable star pattern within a constellation (or sometimes spanning parts of several constellations). For example, the Big Dipper is an asterism within the constellation of Ursa Major, the Big Bear.

Students are sometimes puzzled because the constellations seldom resemble the people or animals for which they were named. In all likelihood, the Greeks themselves did not name groupings of stars because they looked like actual people or subjects (any more than the outline of Washington state resembles George Washington). Rather, they named sections of the sky in honor of the characters in their mythology and then fit the star configurations to the animals and people as best they could.

Link to Learning

This website about objects in the sky allows users to construct a detailed sky map showing the location and information about the Sun, Moon, planets, stars, constellations, and even satellites orbiting Earth. Begin by setting your observing location using the option in the menu in the upper right corner of the screen. An excellent website called Figures in the Sky shows the constellation figures imagined by cultures around the world.

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3.3: Ancient Astronomy

Learning Objectives

By the end of this section, you will be able to:

- Describe early examples of astronomy around the world
- Explain how Greek astronomers were able to deduce that Earth is spherical
- Explain how Greek astronomers were able to calculate Earth's size
- Describe the motion of Earth called precession
- Describe Ptolemy's geocentric system of planetary motion

Let us now look briefly back into history. Much of modern Western civilization is derived in one way or another from the ideas of the ancient Greeks and Romans, and this is true in astronomy as well. However, many other ancient cultures also developed sophisticated systems for observing and interpreting the sky.

Astronomy around the World

Ancient Babylonian, Assyrian, and Egyptian astronomers knew the approximate length of the year. The Egyptians of 3000 years ago, for example, adopted a calendar based on a 365-day year. They kept careful track of the rising time of the bright star Sirius in the predawn sky, which has a yearly cycle that corresponded with the flooding of the Nile River. The Chinese also had a working calendar; they determined the length of the year at about the same time as the Egyptians. The Chinese also recorded comets, bright meteors, and dark spots on the Sun. (Many types of astronomical objects were introduced in Science and the Universe: A Brief Tour. If you are not familiar with terms like *comets* and *meteors*, you may want to review that chapter.) Later, Chinese astronomers kept careful records of "guest stars"—those that are normally too faint to see but suddenly flare up to become visible to the unaided eye for a few weeks or months. We still use some of these records in studying stars that exploded a long time ago.

The Mayan culture in Mexico and Central America developed a sophisticated calendar based on the planet Venus, and they made astronomical observations from sites dedicated to this purpose a thousand years ago. The Polynesians learned to navigate by the stars over hundreds of kilometers of open ocean—a skill that enabled them to colonize new islands far away from where they began.

In Britain, before the widespread use of writing, ancient people used stones to keep track of the motions of the Sun and Moon. We still find some of the great stone circles they built for this purpose, dating from as far back as 2800 BCE. The best known of these is Stonehenge, which is discussed in Earth, Moon, and Sky.[1]

Early Greek and Roman Cosmology

Our concept of the cosmos—its basic structure and origin—is called cosmology, a word with Greek roots. Before the invention of telescopes, humans had to depend on the simple evidence of their senses for a picture of the universe. The ancients developed cosmologies that combined their direct view of the heavens with a rich variety of philosophical and religious symbolism.

At least 2000 years before Columbus, educated people in the eastern Mediterranean region knew Earth was round. Belief in a spherical Earth may have stemmed from the time of Pythagoras, a philosopher and mathematician who lived 2500 years ago. He believed circles and spheres to be "perfect forms" and suggested that Earth should therefore be a sphere. As evidence that the gods liked spheres, the Greeks cited the fact that the Moon is a sphere, using evidence we describe later.

The writings of Aristotle (384–322 BCE), the tutor of Alexander the Great, summarize many of the ideas of his day. They describe how the progression of the Moon's phases—its apparent changing shape—results from our seeing different portions of the Moon's sunlit hemisphere as the month goes by (see Earth, Moon, and Sky). Aristotle also knew that the Sun has to be farther away from Earth than is the Moon because occasionally the Moon passed exactly between Earth and the Sun and hid the Sun temporarily from view. We call this a *solar eclipse*.

Aristotle cited convincing arguments that Earth must be round. First is the fact that as the Moon enters or emerges from Earth's shadow during an eclipse of the Moon, the shape of the shadow seen on the Moon is always round (Figure 2.9). Only a spherical object always produces a round shadow. If Earth were a disk, for example, there would be some occasions when the sunlight would strike it edge-on and its shadow on the Moon would be a line.



Figure 2.9 : Earth's Round Shadow. A lunar eclipse occurs when the Moon moves into and out of Earth's shadow. Note the curved shape of the shadow—evidence for a spherical Earth that has been recognized since antiquity. (credit: modification of work by Brian Paczkowski)

As a second argument, Aristotle explained that travelers who go south a significant distance are able to observe stars that are not visible farther north. And the height of the North Star—the star nearest the north celestial pole—decreases as a traveler moves south. On a flat Earth, everyone would see the same stars overhead. The only possible explanation is that the traveler must have moved over a curved surface on Earth, showing stars from a different angle. (See the How Do We Know Earth Is Round? feature for more ideas on proving Earth is round.)

One Greek thinker, Aristarchus of Samos (310–230 BCE), even suggested that Earth was moving around the Sun, but Aristotle and most of the ancient Greek scholars rejected this idea. One of the reasons for their conclusion was the thought that if Earth moved about the Sun, they would be observing the stars from different places along Earth's orbit. As Earth moved along, nearby stars should shift their positions in the sky relative to more distant stars. In a similar way, we see foreground objects appear to move against a more distant background whenever we are in motion. When we ride on a train, the trees in the foreground appear to shift their position relative to distant hills as the train rolls by. Unconsciously, we use this phenomenon all of the time to estimate distances around us.

The apparent shift in the direction of an object as a result of the motion of the observer is called parallax. We call the shift in the apparent direction of a star due to Earth's orbital motion *stellar parallax*. The Greeks made dedicated efforts to observe stellar parallax, even enlisting the aid of Greek soldiers with the clearest vision, but to no avail. The brighter (and presumably nearer) stars just did not seem to shift as the Greeks observed them in the spring and then again in the fall (when Earth is on the opposite side of the Sun).

This meant either that Earth was not moving or that the stars had to be so tremendously far away that the parallax shift was immeasurably small. A cosmos of such enormous extent required a leap of imagination that most ancient philosophers were not prepared to make, so they retreated to the safety of the Earth-centered view, which would dominate Western thinking for nearly two millennia.

Astronomy Basics: How Do We Know Earth Is Round?

In addition to the two ways (from Aristotle's writings) discussed in this chapter, you might also reason as follows:

1. Let's watch a ship leave its port and sail into the distance on a clear day. On a flat Earth, we would just see the ship get smaller and smaller as it sails away. But this isn't what we actually observe. Instead, ships sink below the horizon, with the hull disappearing first and the mast remaining visible for a while longer. Eventually, only the top of the mast can be seen as the ship sails around the curvature of Earth. Finally, the ship disappears under the horizon.
2. The International Space Station circles Earth once every 90 minutes or so. Photographs taken from the shuttle and other satellites show that Earth is round from every perspective.
3. Suppose you made a friend in each time zone of Earth. You call all of them at the same hour and ask, "Where is the Sun?" On a flat Earth, each caller would give you roughly the same answer. But on a round Earth you would find that, for some friends, the Sun would be high in the sky whereas for others it would be rising, setting, or completely out of sight (and this last group of friends would be upset with you for waking them up).

Measurement of Earth by Eratosthenes

The Greeks not only knew Earth was round, but also they were able to measure its size. The first fairly accurate determination of Earth's diameter was made in about 200 BCE by Eratosthenes (276–194 BCE), a Greek living in Alexandria, Egypt. His method was a geometric one, based on observations of the Sun.

The Sun is so distant from us that all the light rays that strike our planet approach us along essentially parallel lines. To see why, look at Figure 2.10. Take a source of light near Earth—say, at position A. Its rays strike different parts of Earth along diverging

paths. From a light source at B, or at C (which is still farther away), the angle between rays that strike opposite parts of Earth is smaller. The more distant the source, the smaller the angle between the rays. For a source infinitely distant, the rays travel along parallel lines.

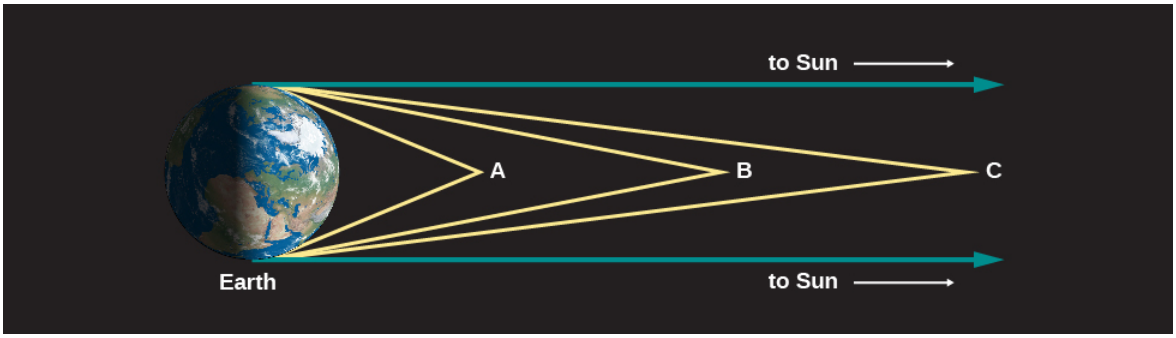


Figure 2.10 : Light Rays from Space. The more distant an object, the more nearly parallel the rays of light coming from it.

Of course, the Sun is not infinitely far away, but given its distance of 150 million kilometers, light rays striking Earth from a point on the Sun diverge from one another by an angle far too small to be observed with the unaided eye. As a consequence, if people all over Earth who could see the Sun were to point at it, their fingers would, essentially, all be parallel to one another. (The same is also true for the planets and stars—an idea we will use in our discussion of how telescopes work.)

Eratosthenes was told that on the first day of summer at Syene, Egypt (near modern Aswan), sunlight struck the bottom of a vertical well at noon. This indicated that the Sun was directly over the well—meaning that Syene was on a direct line from the center of Earth to the Sun. At the corresponding time and date in Alexandria, Eratosthenes observed the shadow a column made and saw that the Sun was not directly overhead, but was slightly south of the zenith, so that its rays made an angle with the vertical equal to about 1/50 of a circle (7°). Because the Sun's rays striking the two cities are parallel to one another, why would the two rays not make the same angle with Earth's surface? Eratosthenes reasoned that the curvature of the round Earth meant that "straight up" was not the same in the two cities. And the measurement of the angle in Alexandria, he realized, allowed him to figure out the size of Earth. Alexandria, he saw, must be 1/50 of Earth's circumference north of Syene (Figure 2.11). Alexandria had been measured to be 5000 stadia north of Syene. (The *stadium* was a Greek unit of length, derived from the length of the racetrack in a stadium.) Eratosthenes thus found that Earth's circumference must be 50×5000, or 250,000 stadia.

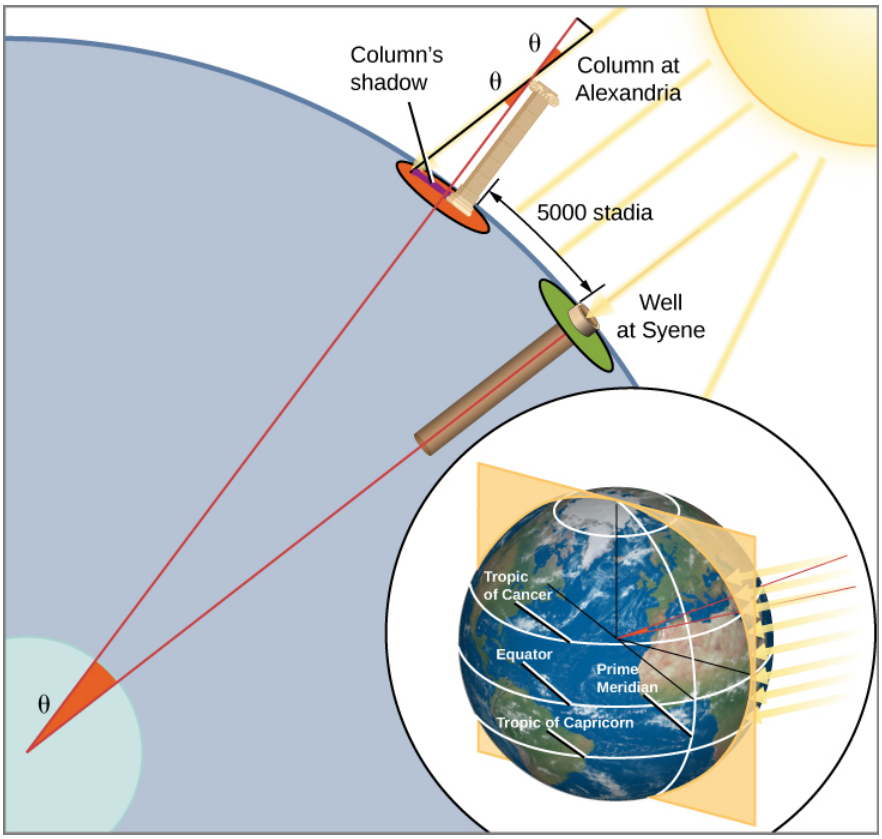


Figure 2.11 : How Eratosthenes Measured the Size of Earth. Eratosthenes measured the size of Earth by observing the angle at which the Sun's rays hit our planet's surface. The Sun's rays come in parallel, but because Earth's surface curves, a ray at Syene comes straight down whereas a ray at Alexandria makes an angle of 7° with the vertical. That means, in effect, that at Alexandria, Earth's surface has curved away from Syene by 7° of 360°, or 1/50 of a full circle. Thus, the distance between the two cities must be 1/50 the circumference of Earth. (credit: modification of work by NOAA Ocean Service Education)

It is not possible to evaluate precisely the accuracy of Eratosthenes solution because there is doubt about which of the various kinds of Greek stadia he used as his unit of distance. If it was the common Olympic stadium, his result is about 20% too large. According to another interpretation, he used a stadium equal to about 1/6 kilometer, in which case his figure was within 1% of the correct value of 40,000 kilometers. Even if his measurement was not exact, his success at measuring the size of our planet by using only shadows, sunlight, and the power of human thought was one of the greatest intellectual achievements in history.

Hipparchus and Precession

Perhaps the greatest astronomer of antiquity was Hipparchus, born in Nicaea in what is present-day Turkey. He erected an observatory on the island of Rhodes around 150 BCE, when the Roman Republic was expanding its influence throughout the Mediterranean region. There he measured, as accurately as possible, the positions of objects in the sky, compiling a pioneering star catalog with about 850 entries. He designated celestial coordinates for each star, specifying its position in the sky, just as we specify the position of a point on Earth by giving its latitude and longitude.

He also divided the stars into apparent magnitudes according to their apparent brightness. He called the brightest ones “stars of the first magnitude”; the next brightest group, “stars of the second magnitude”; and so forth. This rather arbitrary system, in modified form, still remains in use today (although it is less and less useful for professional astronomers).

By observing the stars and comparing his data with older observations, Hipparchus made one of his most remarkable discoveries: the position in the sky of the north celestial pole had altered over the previous century and a half. Hipparchus deduced correctly that this had happened not only during the period covered by his observations, but was in fact happening all the time: the direction around which the sky appears to rotate changes slowly but continuously. Recall from the section on celestial poles and the celestial equator that the north celestial pole is just the projection of Earth’s North Pole into the sky. If the north celestial pole is wobbling around, then Earth itself must be doing the wobbling. Today, we understand that the direction in which Earth’s axis points does indeed change slowly but regularly—a motion we call precession. If you have ever watched a spinning top wobble, you observed a similar kind of motion. The top’s axis describes a path in the shape of a cone, as Earth’s gravity tries to topple it (Figure 2.12).

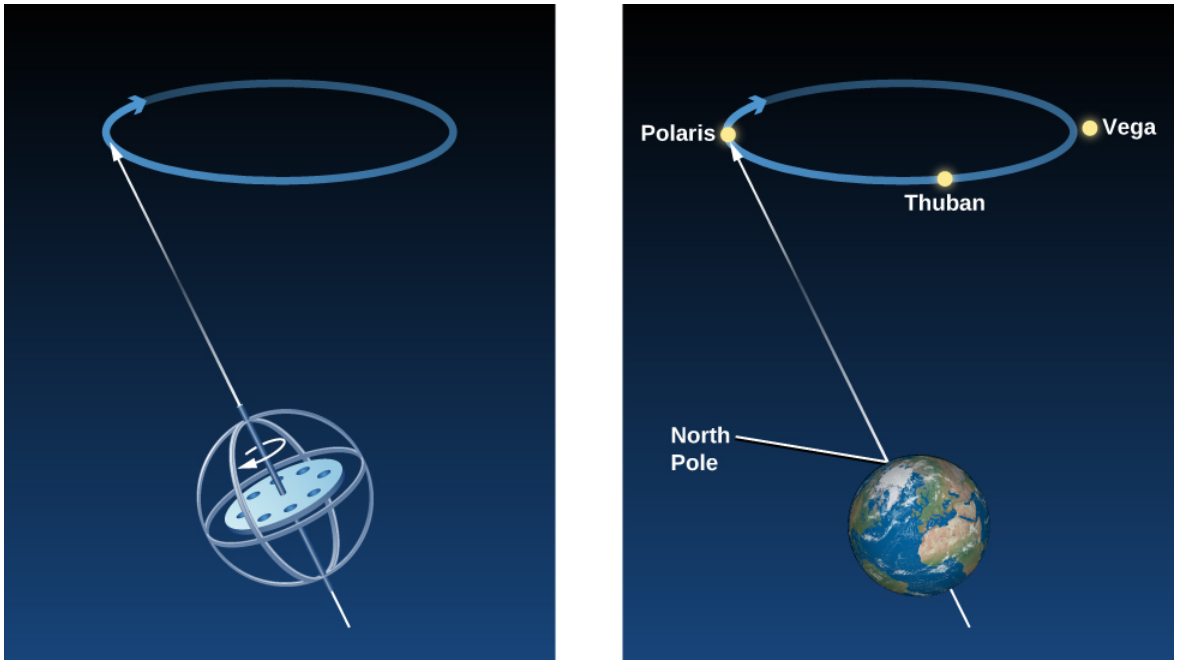


Figure 2.12 : Precession. Just as the axis of a rapidly spinning top wobbles slowly in a circle, so the axis of Earth wobbles in a 26,000-year cycle. Today the north celestial pole is near the star Polaris, but about 5000 years ago it was close to a star called Thuban, and in 14,000 years it will be closest to the star Vega.

Because our planet is not an exact sphere, but bulges a bit at the equator, the pulls of the Sun and Moon cause it to wobble like a top. It takes about 26,000 years for Earth’s axis to complete one circle of precession. As a result of this motion, the point where our axis points in the sky changes as time goes on. While Polaris is the star closest to the north celestial pole today (it will reach its closest point around the year 2100), the star Vega in the constellation of Lyra will be the North Star in 14,000 years.

Ptolemy's Model of the Solar System

The last great astronomer of the Roman era was Claudius Ptolemy (or Ptolemaeus), who flourished in Alexandria in about the year 140. He wrote a mammoth compilation of astronomical knowledge, which today is called by its Arabic name, *Almagest* (meaning "The Greatest"). *Almagest* does not deal exclusively with Ptolemy's own work; it includes a discussion of the astronomical achievements of the past, principally those of Hipparchus. Today, it is our main source of information about the work of Hipparchus and other Greek astronomers.

Ptolemy's most important contribution was a geometric representation of the solar system that predicted the positions of the planets for any desired date and time. Hipparchus, not having enough data on hand to solve the problem himself, had instead amassed observational material for posterity to use. Ptolemy supplemented this material with new observations of his own and produced a cosmological model that endured more than a thousand years, until the time of Copernicus.

The complicating factor in explaining the motions of the planets is that their apparent wandering in the sky results from the combination of their own motions with Earth's orbital revolution. As we watch the planets from our vantage point on the moving Earth, it is a little like watching a car race while you are competing in it. Sometimes opponents' cars pass you, but at other times you pass them, making them appear to move backward for a while with respect to you.

Figure 2.13 shows the motion of Earth and a planet farther from the Sun—in this case, Mars. Earth travels around the Sun in the same direction as the other planet and in nearly the same plane, but its orbital speed is faster. As a result, it overtakes the planet periodically, like a faster race car on the inside track. The figure shows where we see the planet in the sky at different times. The path of the planet among the stars is illustrated in the star field on the right side of the figure.

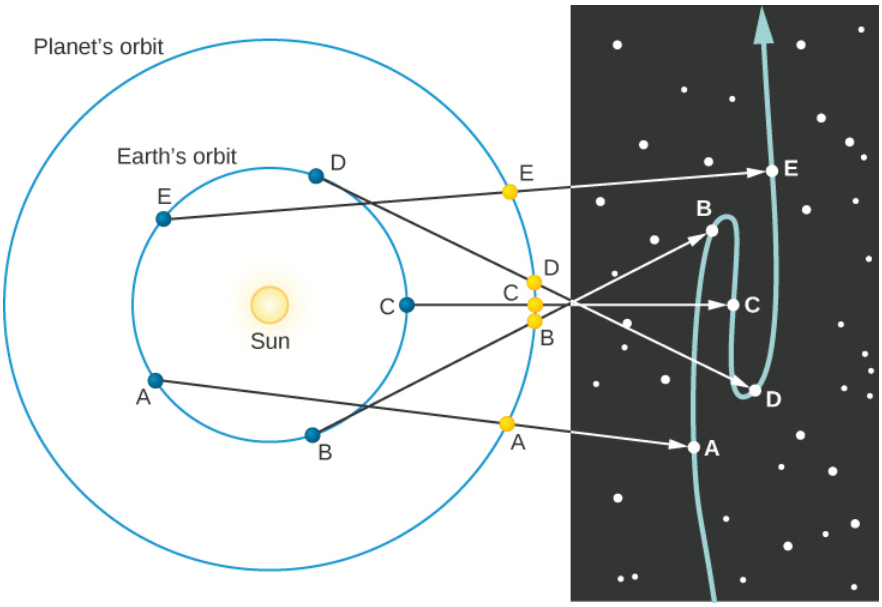


Figure 2.13 : Retrograde Motion of a Planet beyond Earth's Orbit. The letters on the diagram show where Earth and Mars are at different times. By following the lines from each Earth position through each corresponding Mars position, you can see how the retrograde path of Mars looks against the background stars.

Link to Learning

The planetary configurations simulator from Foothill AstroSims allows you to see the usual prograde and occasional retrograde motion of other planets. You can switch back and forth between viewing motion from Earth and Mars (as well as other planets).

Normally, planets move eastward in the sky over the weeks and months as they orbit the Sun, but from positions B to D in Figure 2.13, as Earth passes the planets in our example, it appears to drift backward, moving west in the sky. Even though it is actually moving to the east, the faster-moving Earth has overtaken it and seems, from our perspective, to be leaving it behind. As Earth rounds its orbit toward position E, the planet again takes up its apparent eastward motion in the sky. The temporary apparent westward motion of a planet as Earth swings between it and the Sun is called retrograde motion. Such backward motion is much

easier for us to understand today, now that we know Earth is one of the moving planets and not the unmoving center of all creation. But Ptolemy was faced with the far more complex problem of explaining such motion while assuming a stationary Earth.

Furthermore, because the Greeks believed that celestial motions had to be circles, Ptolemy had to construct his model using circles alone. To do it, he needed dozens of circles, some moving around other circles, in a complex structure that makes a modern viewer dizzy. But we must not let our modern judgment cloud our admiration for Ptolemy's achievement. In his day, a complex universe centered on Earth was perfectly reasonable and, in its own way, quite beautiful. However, as Alfonso X, the King of Castile, was reported to have said after having the Ptolemaic system of planet motions explained to him, "If the Lord Almighty had consulted me before embarking upon Creation, I should have recommended something simpler."

Ptolemy solved the problem of explaining the observed motions of planets by having each planet revolve in a small orbit called an epicycle. The center of the epicycle then revolved about Earth on a circle called a *deferent* (Figure 2.14). When the planet is at position *x* in Figure 2.14 on the epicycle orbit, it is moving in the same direction as the center of the epicycle; from Earth, the planet appears to be moving eastward. When the planet is at *y*, however, its motion is in the direction opposite to the motion of the epicycle's center around Earth. By choosing the right combination of speeds and distances, Ptolemy succeeded in having the planet moving westward at the correct speed and for the correct interval of time, thus replicating retrograde motion with his model.

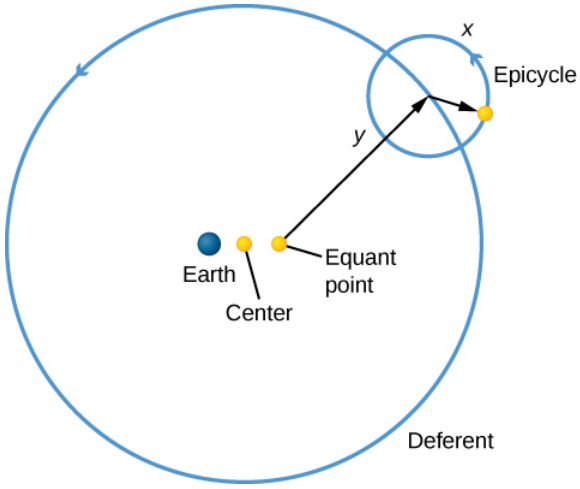


Figure 2.14 : Ptolemy's Complicated Cosmological System. Each planet orbits around a small circle called an *epicycle*. Each epicycle orbits on a larger circle called the *deferent*. This system is not centered exactly on Earth but on an offset point called the *equant*. The Greeks needed all this complexity to explain the actual motions in the sky because they believed that Earth was stationary and that all sky motions had to be circular.

Link to Learning

Use the Ptolemaic System simulator from Foothill AstroSims to explore how Ptolemy's system of deferents and epicycles explained the apparent motion of the planets.

However, we shall see in Orbits and Gravity that the planets, like Earth, travel about the Sun in orbits that are ellipses, not circles. Their actual behavior cannot be represented accurately by a scheme of uniform circular motions. In order to match the observed motions of the planets, Ptolemy had to center the deferent circles, not on Earth, but at points some distance from Earth. In addition, he introduced uniform circular motion around yet another axis, called the *equant point*. All of these considerably complicated his scheme.

It is a tribute to the genius of Ptolemy as a mathematician that he was able to develop such a complex system to account successfully for the observations of planets. It may be that Ptolemy did not intend for his cosmological model to describe reality, but merely to serve as a mathematical representation that allowed him to predict the positions of the planets at any time. Whatever his thinking, his model, with some modifications, was eventually accepted as authoritative in the Muslim world and (later) in Christian Europe.

Footnotes

- 1For resources providing more information about the astronomy of diverse cultures around the world, please see http://bit.ly/astrocultures.

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3.4: Astrology and Astronomy

Learning Objectives

By the end of this section, you will be able to:

- Explain the origins of astrology
- Explain what a horoscope is
- Summarize the arguments that invalidate astrology as a scientific practice

Many ancient cultures regarded the planets and stars as representatives or symbols of the gods or other supernatural forces that controlled their lives. For them, the study of the heavens was not an abstract subject; it was connected directly to the life-and-death necessity of understanding the actions of the gods and currying favor with them. Before the time of our scientific perspectives, everything that happened in nature—from the weather, to diseases and accidents, to celestial surprises such as eclipses or new comets—was thought to be an expression of the whims or displeasure of the gods. Any signs that helped people understand what these gods had in mind were considered extremely important.

The movements of the seven objects that had the power to "wander" through the realm of the sky—the Sun, the Moon, and five planets visible to the unaided eye—clearly must have special significance in such a system of thinking.

Most ancient cultures associated these seven objects with various supernatural rulers in their pantheon and kept track of them for religious reasons. Even in the comparatively sophisticated Greece of antiquity, the planets had the names of gods and were credited with having the same powers and influences as the gods whose names they bore. From such ideas was born the ancient system called astrology, still practiced by some people today, in which the positions of these bodies among the stars of the zodiac are thought to hold the key to understanding what we can expect from life.

The Beginnings of Astrology

Astrology began in Babylonia about two and half millennia ago. The Babylonians, believing the planets and their motions influenced the fortunes of kings and nations, used their knowledge of astronomy to guide their rulers. When the Babylonian culture was absorbed by the Greeks, astrology gradually came to influence the entire Western world and eventually spread to Asia as well.

By the 2nd century BCE the Greeks democratized astrology by developing the idea that the planets influence every individual. In particular, they believed that the configuration of the Sun, Moon, and planets at the moment of birth affected a person's personality and fortune—a doctrine called *natal astrology*. Natal astrology reached its peak with Ptolemy 400 years later. As famous for his astrology as for his astronomy, Ptolemy compiled the *Tetrabiblos*, a treatise on astrology that remains the "bible" of the subject. It is essentially this ancient religion, older than Christianity or Islam, that is still practiced by today's astrologers.

The Horoscope

The key to natal astrology is the horoscope, a chart showing the positions of the planets in the sky at the moment of an individual's birth. The word "horoscope" comes from the Greek words *hora* (meaning "time") and *skopos* (meaning a "watcher" or "marker"), so "horoscope" can literally be translated as "marker of the hour." When a horoscope is charted, the planets (including the Sun and Moon, classed as *wanderers* by the ancients) must first be located in the zodiac. At the time astrology was set up, the zodiac was divided into 12 sectors called *signs* (Figure 2.15), each 30° long. Each sign was named after a constellation in the sky through which the Sun, Moon, and planets were seen to pass—the sign of Virgo after the constellation of Virgo, for example.

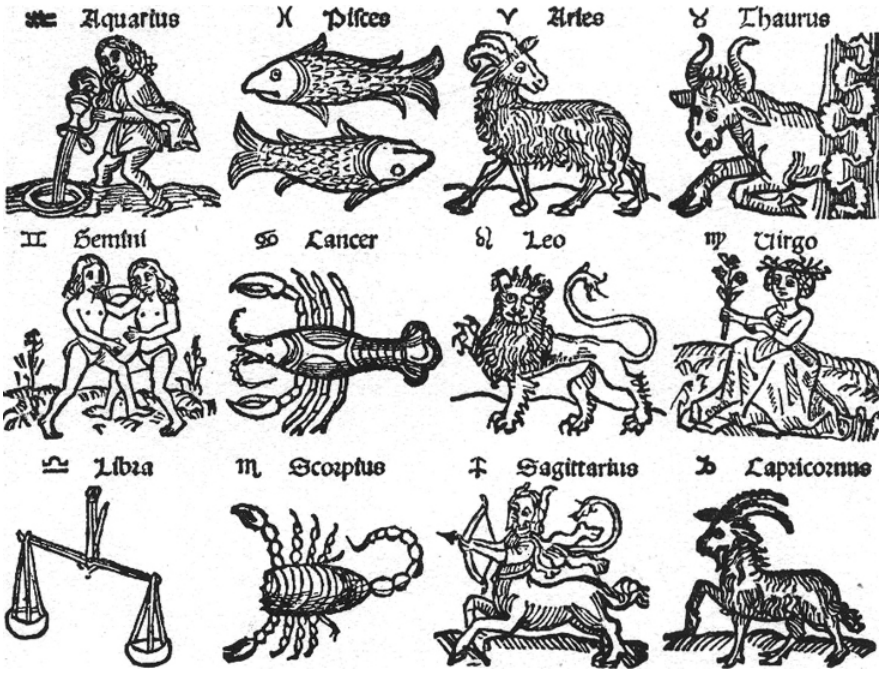


Figure 2.15 : Zodiac Signs. The signs of the zodiac are shown in a medieval woodcut.

When someone today casually asks you your “sign,” they are asking for your “sun sign”—which zodiac sign the Sun was in at the moment you were born. However, more than 2000 years have passed since the signs received their names from the constellations. Because of precession, the constellations of the zodiac slide westward along the ecliptic, going once around the sky in about 26,000 years. Thus, today the real stars have slipped around by about 1/12 of the zodiac—about the width of one sign.

In most forms of astrology, however, the signs have remained assigned to the dates of the year they had when astrology was first set up. This means that the astrological signs and the real constellations are out of step; the sign of Aries, for example, now occupies the constellation of Pisces. When you look up your sun sign in a newspaper astrology column, the name of the sign associated with your birthday is no longer the name of the constellation in which the Sun was actually located when you were born. To know that constellation, you must look for the sign before the one that includes your birthday.

A complete horoscope shows the location of not only the Sun, but also the Moon and each planet in the sky by indicating its position in the appropriate sign of the zodiac. However, as the celestial sphere turns (owing to the rotation of Earth), the entire zodiac moves across the sky to the west, completing a circuit of the heavens each day. Thus, the position in the sky (or “house” in astrology) must also be calculated. There are more or less standardized rules for the interpretation of the horoscope, most of which (at least in Western schools of astrology) are derived from the *Tetrabiblos* of Ptolemy. Each sign, each house, and each planet—the last acting as a center of force—is supposed to be associated with particular matters in a person’s life.

The detailed interpretation of a horoscope is a very complicated business, and there are many schools of astrological thought on how it should be done. Although some of the rules may be standardized, how each rule is to be weighed and applied is a matter of judgment—and “art.” It also means that it is very difficult to tie down astrology to specific predictions or to get the same predictions from different astrologers.

Astrology Today

Astrologers today use the same basic principles laid down by Ptolemy nearly 2000 years ago. They cast horoscopes (a process much simplified by the development of appropriate computer programs) and suggest interpretations. Sun sign astrology (which you read in the newspapers and many magazines) is a recent, simplified variant of natal astrology. Although even professional astrologers do not place much trust in such a limited scheme, which tries to fit everyone into just 12 groups, sun sign astrology is taken seriously by many people (perhaps because it is discussed so commonly in the media).

Today, we know much more about the nature of the planets as physical bodies, as well as about human genetics, than the ancients could. It is hard to imagine how the positions of the Sun, Moon, or planets in the sky at the moment of our birth could have anything to do with our personality or future. There are no known forces, not gravity or anything else, that could cause such effects. (For example, a straightforward calculation shows that the gravitational pull of the obstetrician delivering a newborn baby is greater than that of Mars.) Astrologers thus have to argue there must be unknown forces exerted by the planets that depend on their configurations with respect to one another and that do not vary according to the distance of the planet—forces for which there is no shred of evidence.

Another curious aspect of astrology is its emphasis on planet configurations at birth. What about the forces that might influence us at conception? Isn't our genetic makeup more important for determining our personality than the circumstances of our birth? Would we really be a different person if we had been born a few hours earlier or later, as astrology claims? (Back when astrology was first conceived, birth was thought of as a moment of magic significance, but today we understand a lot more about the long process that precedes it.)

Actually, very few well-educated people today buy the claim that our entire lives are predetermined by astrological influences at birth, but many people apparently believe that astrology has validity as an indicator of affinities and personality. A surprising number of Americans make judgments about people—whom they will hire, associate with, and even marry—on the basis of astrological information. To be sure, these are difficult decisions, and you might argue that we should use any relevant information that might help us to make the right choices. But does astrology actually provide any useful information on human personality? This is the kind of question that can be tested using the scientific method (see Testing Astrology).

The results of hundreds of tests are all the same: there is no evidence that natal astrology has any predictive power, even in a statistical sense. Why, then, do people often seem to have anecdotes about how well their own astrologer advised them? Effective astrologers today use the language of the zodiac and the horoscope only as the outward trappings of their craft. Mostly they work as amateur therapists, offering simple truths that clients like or need to hear. (Recent studies have shown that just about any sort of short-term therapy makes people feel a little better because the very act of talking about our problems with someone who listens attentively is, in itself, beneficial.)

The scheme of astrology has no basis in scientific fact, however; at best, it can be described as a pseudoscience. It is an interesting historical system, left over from prescientific days and best remembered for the impetus it gave people to learn the cycles and patterns of the sky. From it grew the science of astronomy, which is our main subject for discussion.

Making Connections: Testing Astrology

In response to modern public interest in astrology, scientists have carried out a wide range of statistical tests to assess its predictive power. The simplest of these examine sun sign astrology to determine whether—as astrologers assert—some signs are more likely than others to be associated with some objective measure of success, such as winning Olympic medals, earning high corporate salaries, or achieving elective office or high military rank. (You can devise such a test yourself by looking up the birth dates of all members of Congress, for example, or all members of the U.S. Olympic team.) Are our political leaders somehow selected at birth by their horoscopes and thus more likely to be Leos, say, than Scorpios?

You do not even need to be specific about your prediction in such tests. After all, many practitioners of astrology disagree about which signs go with which personality characteristics. To demonstrate the validity of the astrological hypothesis, it would be sufficient if the birthdays of all our leaders clustered in any one or two signs in some statistically significant way. Dozens of such tests have been performed, and all have come up completely negative: the birth dates of leaders in all fields tested have been found to be distributed randomly among *all* the signs. Sun sign astrology does not predict anything about a person's future occupation or strong personality traits.

In a fine example of such a test, two statisticians examined the reenlistment records of the United States Marine Corps. We suspect you will agree that it takes a certain kind of personality not only to enlist, but also to reenlist in the Marines. If sun

signs can predict strong personality traits—as astrologers claim—then those who reenlisted (with similar personalities) should have been distributed preferentially in those one or few signs that matched the personality of someone who loves being a Marine. However, the reenlisted were distributed randomly among all the signs.

More sophisticated studies have also been done, involving full horoscopes calculated for thousands of individuals. The results of all these studies are also negative: none of the systems of astrology has been shown to be at all effective in connecting astrological aspects to personality, success, or finding the right person to love.

Other tests show that it hardly seems to matter what a horoscope interpretation says, as long as it is vague enough, and as long as each subject feels it was prepared personally just for him or her. The French statistician Michel Gauquelin, for example, sent the horoscope interpretation for one of the worst mass murderers in history to 150 people, but told each recipient that it was a "reading" prepared exclusively for him or her. Ninety-four percent of the readers said they recognized themselves in the interpretation of the mass murderer's horoscope.

Geoffrey Dean, an Australian researcher, reversed the astrological readings of 22 subjects, substituting phrases that were the opposite of what the horoscope actually said. Yet, his subjects said that the resulting readings applied to them just as often (95%) as the people to whom the original phrases were given.

Link to Learning

For more on astrology and science from an astronomer's point of view, read this article that shines light on the topic through an accessible Q&A.

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3.5: The Birth of Modern Astronomy

Learning Objectives

By the end of this section, you will be able to:

- Explain how Copernicus developed the heliocentric model of the solar system
- Explain the Copernican model of planetary motion and describe evidence or arguments in favor of it
- Describe Galileo's discoveries concerning the study of motion and forces
- Explain how Galileo's discoveries tilted the balance of evidence in favor of the Copernican model

Astronomy made no major advances in strife-torn medieval Europe. The birth and expansion of Islam after the seventh century led to a flowering of Arabic and Jewish cultures that preserved, translated, and added to many of the astronomical ideas of the Greeks. Many of the names of the brightest stars, for example, are today taken from the Arabic, as are such astronomical terms as "zenith."

As European culture began to emerge from its long, dark age, trading with Arab countries led to a rediscovery of ancient texts such as *Almagest* and to a reawakening of interest in astronomical questions. This time of rebirth (in French, "*renaissance*") in astronomy was embodied in the work of Copernicus (Figure 2.16).

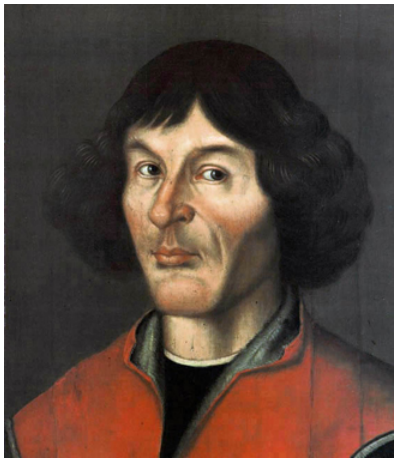


Figure 2.16 : Nicolaus Copernicus (1473–1543). Copernicus was a cleric and scientist who played a leading role in the emergence of modern science. Although he could not prove that Earth revolves about the Sun, he presented such compelling arguments for this idea that he turned the tide of cosmological thought and laid the foundations upon which Galileo and Kepler so effectively built in the following century.

Copernicus

One of the most important events of the Renaissance was the displacement of Earth from the center of the universe, an intellectual revolution initiated by a Polish cleric in the sixteenth century. Nicolaus Copernicus was born in Torun, a mercantile town along the Vistula River. His training was in law and medicine, but his main interests were astronomy and mathematics. His great contribution to science was a critical reappraisal of the existing theories of planetary motion and the development of a new Sun-centered, or heliocentric, model of the solar system. Copernicus concluded that Earth is a planet and that all the planets circle the Sun. Only the Moon orbits Earth (Figure 2.17).

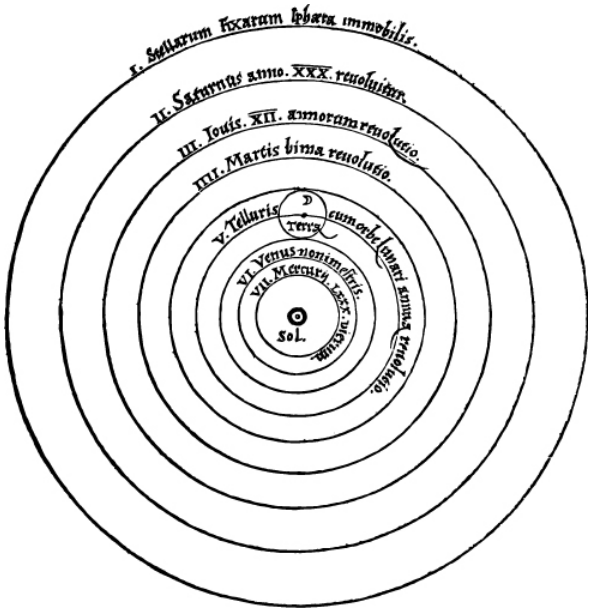


Figure 2.17 : Copernicus' System. Copernicus developed a heliocentric plan of the solar system. This system was published in the first edition of *De Revolutionibus Orbium Coelestium*. Notice the word *Sol* for "Sun" in the middle. (credit: Nicolai Copernici)

Copernicus described his ideas in detail in his book *De Revolutionibus Orbium Coelestium* (*On the Revolution of Celestial Orbs*), published in 1543, the year of his death. By this time, the old Ptolemaic system needed significant adjustments to predict the positions of the planets correctly. Copernicus wanted to develop an improved theory from which to calculate planetary positions, but in doing so, he was himself not free of all traditional prejudices.

He began with several assumptions that were common in his time, such as the idea that the motions of the heavenly bodies must be made up of combinations of uniform circular motions. But he did not assume (as most people did) that Earth had to be in the center of the universe, and he presented a defense of the heliocentric system that was elegant and persuasive. His ideas, although not widely accepted until more than a century after his death, were much discussed among scholars and, ultimately, had a profound influence on the course of world history.

One of the objections raised to the heliocentric theory was that if Earth were moving, we would all sense or feel this motion. Solid objects would be ripped from the surface, a ball dropped from a great height would not strike the ground directly below it, and so forth. But a moving person is not necessarily aware of that motion. We have all experienced seeing an adjacent train, bus, or ship appear to move, only to discover that it is we who are moving.

Copernicus argued that the apparent motion of the Sun about Earth during the course of a year could be represented equally well by a motion of Earth about the Sun. He also reasoned that the apparent rotation of the celestial sphere could be explained by assuming that Earth rotates while the celestial sphere is stationary. To the objection that if Earth rotated about an axis it would fly into pieces, Copernicus answered that if such motion would tear Earth apart, the still faster motion of the much larger celestial sphere required by the geocentric hypothesis would be even more devastating.

The Heliocentric Model

The most important idea in Copernicus' *De Revolutionibus* is that Earth is one of six (then-known) planets that revolve about the Sun. Using this concept, he was able to work out the correct general picture of the solar system. He placed the planets, starting nearest the Sun, in the correct order: Mercury, Venus, Earth, Mars, Jupiter, and Saturn. Further, he deduced that the nearer a planet is to the Sun, the greater its orbital speed. With his theory, he was able to explain the complex retrograde motions of the planets without epicycles and to work out a roughly correct scale for the solar system.

Copernicus could not prove that Earth revolves about the Sun. In fact, with some adjustments, the old Ptolemaic system could have accounted, as well, for the motions of the planets in the sky. But Copernicus pointed out that the Ptolemaic cosmology was clumsy and lacking the beauty and symmetry of its successor.

In Copernicus' time, in fact, few people thought there were ways to prove whether the heliocentric or the older geocentric system was correct. A long philosophical tradition, going back to the Greeks and defended by the Catholic Church, held that pure human thought combined with divine revelation represented the path to truth. Nature, as revealed by our senses, was suspect. For example, Aristotle had reasoned that heavier objects (having more of the quality that made them heavy) must fall to Earth faster than lighter ones. This is absolutely incorrect, as any simple experiment dropping two balls of different weights shows. However, in Copernicus' day, experiments did not carry much weight (if you will pardon the expression); Aristotle's reasoning was more convincing.

In this environment, there was little motivation to carry out observations or experiments to distinguish between competing cosmological theories (or anything else). It should not surprise us, therefore, that the heliocentric idea was debated for more than half a century without any tests being applied to determine its validity. (In fact, in the North American colonies, the older geocentric system was still taught at Harvard University in the first years after it was founded in 1636.)

Contrast this with the situation today, when scientists rush to test each new hypothesis and do not accept any ideas until the results are in. For example, when two researchers at the University of Utah announced in 1989 that they had discovered a way to achieve nuclear fusion (the process that powers the stars) at room temperature, other scientists at more than 25 laboratories around the United States attempted to duplicate "cold fusion" within a few weeks—without success, as it turned out. The cold fusion theory soon went down in flames.

How would we look at Copernicus' model today? When a new hypothesis or theory is proposed in science, it must first be checked for consistency with what is already known. Copernicus' heliocentric idea passes this test, for it allows planetary positions to be calculated at least as well as does the geocentric theory. The next step is to determine which predictions the new hypothesis makes that differ from those of competing ideas. In the case of Copernicus, one example is the prediction that, if Venus circles the Sun, the planet should go through the full range of phases just as the Moon does, whereas if it circles Earth, it should not (Figure 2.18). Also, we should not be able to see the full phase of Venus from Earth because the Sun would then be between Venus and Earth. But in those days, before the telescope, no one imagined testing these predictions.

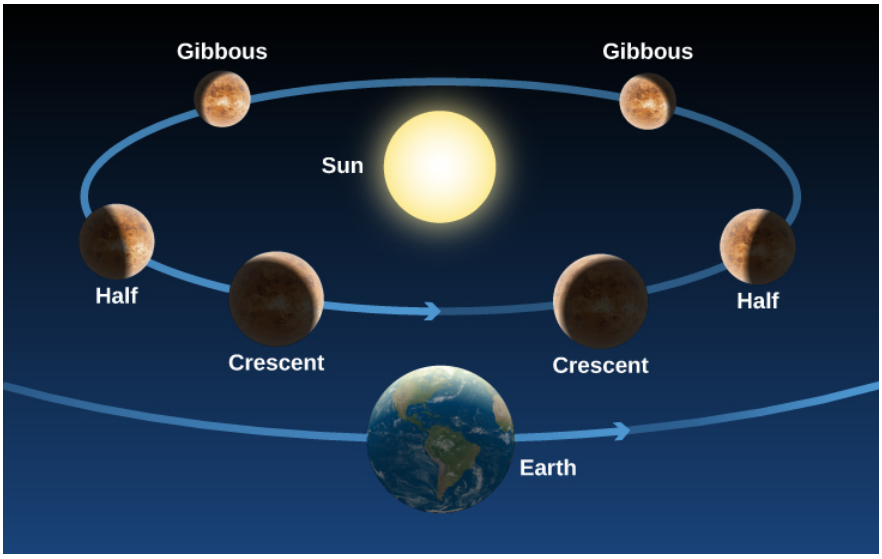


Figure 2.18 : Phases of Venus. As Venus moves around the Sun, we see changing illumination of its surface, just as we see the face of the Moon illuminated differently in the course of a month.

Link to Learning

This animation shows the phases of Venus. You can also see its distance from Earth as it orbits the Sun.

Galileo and the Beginning of Modern Science

Many of the modern scientific concepts of observation, experimentation, and the testing of hypotheses through careful quantitative measurements were pioneered by a man who lived nearly a century after Copernicus. Galileo Galilei (Figure 2.19), a contemporary of Shakespeare, was born in Pisa. Like Copernicus, he began training for a medical career, but he had little interest in the subject and later switched to mathematics. He held faculty positions at the University of Pisa and the University of Padua, and eventually became mathematician to the Grand Duke of Tuscany in Florence.



Figure 2.19 : Galileo Galilei (1564–1642). Galileo advocated that we perform experiments or make observations to ask nature its ways. When Galileo turned the telescope to the sky, he found things were not the way philosophers had supposed.

Galileo's greatest contributions were in the field of mechanics, the study of motion and the actions of forces on bodies. It was familiar to all persons then, as it is to us now, that if something is at rest, it tends to remain at rest and requires some outside influence to start it in motion. Rest was thus generally regarded as the natural state of matter. Galileo showed, however, that rest is no more natural than motion.

If an object is slid along a rough horizontal floor, it soon comes to rest because friction between it and the floor acts as a retarding force. However, if the floor and the object are both highly polished, the object, given the same initial speed, will slide farther before stopping. On a smooth layer of ice, it will slide farther still. Galileo reasoned that if all resisting effects could be removed, the object would continue in a steady state of motion indefinitely. He argued that a force is required not only to start an object moving from rest but also to slow down, stop, speed up, or change the direction of a moving object. You will appreciate this if you have ever tried to stop a rolling car by leaning against it, or a moving boat by tugging on a line.

Galileo also studied the way objects accelerate—change their speed or direction of motion. Galileo watched objects as they fell freely or rolled down a ramp. He found that such objects accelerate uniformly; that is, in equal intervals of time they gain equal increments in speed. Galileo formulated these newly found laws in precise mathematical terms that enabled future experimenters to predict how far and how fast objects would move in various lengths of time.

Link to Learning

In theory, if Galileo is right, a feather and a hammer, dropped at the same time from a height, should land at the same moment. On Earth, this experiment is not possible because air resistance and air movements make the feather flutter, instead of falling straight down, accelerated only by the force of gravity. For generations, physics teachers had said that the place to try this experiment is somewhere where there is no air, such as the Moon. In 1971, *Apollo 15* astronaut David Scott took a hammer and feather to the Moon and tried it, to the delight of physics nerds everywhere. NASA provides the video of the hammer and feather as well as a brief explanation.

Sometime in the 1590s, Galileo adopted the Copernican hypothesis of a heliocentric solar system. In Roman Catholic Italy, this was not a popular philosophy, for Church authorities still upheld the ideas of Aristotle and Ptolemy, and they had powerful political and economic reasons for insisting that Earth was the center of creation. Galileo not only challenged this thinking but also had the audacity to write in Italian rather than scholarly Latin, and to lecture publicly on those topics. For him, there was no contradiction between the authority of the Church in matters of religion and morality, and the authority of nature (revealed by experiments) in matters of science. It was primarily because of Galileo and his "dangerous" opinions that, in 1616, the Church issued a prohibition decree stating that the Copernican doctrine was "false and absurd" and not to be held or defended.

Galileo's Astronomical Observations

It is not certain who first conceived of the idea of combining two or more pieces of glass to produce an instrument that enlarged images of distant objects, making them appear nearer. The first such "spyglasses" (now called *telescopes*) that attracted much notice were made in 1608 by the Dutch spectacle maker Hans Lippershey (1570–1619). Galileo heard of the discovery and, without ever having seen an assembled telescope, constructed one of his own with a three-power magnification (3×), which made distant objects appear three times nearer and larger (Figure 2.20).



Figure 2.20 : Telescope Used by Galileo. The telescope has a wooden tube covered with paper and a lens 26 millimeters across.

On August 25, 1609, Galileo demonstrated a telescope with a magnification of 9× to government officials of the city-state of Venice. By a magnification of 9×, we mean the linear dimensions of the objects being viewed appeared nine times larger or, alternatively, the objects appeared nine times closer than they really were. There were obvious military advantages associated with a device for seeing distant objects. For his invention, Galileo's salary was nearly doubled, and he was granted lifetime tenure as a professor. (His university colleagues were outraged, particularly because the invention was not even original.)

Others had used the telescope before Galileo to observe things on Earth. But in a flash of insight that changed the history of astronomy, Galileo realized that he could turn the power of the telescope toward the heavens. Before using his telescope for astronomical observations, Galileo had to devise a stable mount and improve the optics. He increased the magnification to 30×. Galileo also needed to acquire confidence in the telescope.

At that time, human eyes were believed to be the final arbiter of truth about size, shape, and color. Lenses, mirrors, and prisms were known to distort distant images by enlarging, reducing, or inverting them, or spreading the light into a spectrum (rainbow of colors). Galileo undertook repeated experiments to convince himself that what he saw through the telescope was identical to what he saw up close. Only then could he begin to believe that the miraculous phenomena the telescope revealed in the heavens were real.

Beginning his astronomical work late in 1609, Galileo found that many stars too faint to be seen with the unaided eye became visible with his telescope. In particular, he found that some nebulous blurs resolved into many stars, and that the Milky Way—the strip of whiteness across the night sky—was also made up of a multitude of individual stars.

Examining the planets, Galileo found four moons revolving about Jupiter in times ranging from just under 2 days to about 17 days. This discovery was particularly important because it showed that not everything has to revolve around Earth. Furthermore, it demonstrated that there could be centers of motion that are themselves in motion. Defenders of the geocentric view had argued that if Earth was in motion, then the Moon would be left behind because it could hardly keep up with a rapidly moving planet. Yet, here were Jupiter's moons doing exactly that. (To recognize this discovery and honor his work, NASA named a spacecraft that explored the Jupiter system Galileo.)

With his telescope, Galileo was able to carry out the test of the Copernican theory mentioned earlier, based on the phases of Venus. Within a few months, he had found that Venus goes through phases like the Moon, showing that it must revolve about the Sun, so that we see different parts of its daylight side at different times (see Figure 2.18.) These observations could not be reconciled with Ptolemy's model, in which Venus circled about Earth. In Ptolemy's model, Venus could also show phases, but they were the wrong phases in the wrong order from what Galileo observed.

Galileo also observed the Moon and saw craters, mountain ranges, valleys, and flat, dark areas that he thought might be water. These discoveries showed that the Moon might be not so dissimilar to Earth—suggesting that Earth, too, could belong to the realm of celestial bodies.

Link to Learning

For more information about the life and work of Galileo, see the Galileo Project at Rice University.

After Galileo's work, it became increasingly difficult to deny the Copernican view, and Earth was slowly dethroned from its central position in the universe and given its rightful place as one of the planets attending the Sun. Initially, however, Galileo met with a great deal of opposition. The Roman Catholic Church, still reeling from the Protestant Reformation, was looking to assert its authority and chose to make an example of Galileo. He had to appear before the Inquisition to answer charges that his work was heretical, and he was ultimately condemned to house arrest. His books were on the Church's forbidden list until 1836, although in countries where the Roman Catholic Church held less sway, they were widely read and discussed. Not until 1992 did the Catholic Church admit publicly that it had erred in the matter of censoring Galileo's ideas.

The new ideas of Copernicus and Galileo began a revolution in our conception of the cosmos. It eventually became evident that the universe is a vast place and that Earth's role in it is relatively unimportant. The idea that Earth moves around the Sun like the other planets raised the possibility that they might be worlds themselves, perhaps even supporting life. As Earth was demoted from its position at the center of the universe, so, too, was humanity. The universe, despite what we may wish, does not revolve around us.

Most of us take these things for granted today, but four centuries ago such concepts were frightening and heretical for some, immensely stimulating for others. The pioneers of the Renaissance started the European world along the path toward science and technology that we still tread today. For them, nature was rational and ultimately knowable, and experiments and observations provided the means to reveal its secrets.

Seeing for Yourself: Observing the Planets

At most any time of the night, and at any season, you can spot one or more bright planets in the sky. All five of the planets known to the ancients—Mercury, Venus, Mars, Jupiter, and Saturn—are more prominent than any but the brightest stars, and they can be seen even from urban locations if you know where and when to look. One way to tell planets from bright stars is that planets twinkle less.

Venus, which stays close to the Sun from our perspective, appears either as an "evening star" in the west after sunset or as a "morning star" in the east before sunrise. It is the brightest object in the sky after the Sun and Moon. It far outshines any real star, and under the most favorable circumstances, it can even cast a visible shadow. Some young military recruits have tried to shoot Venus down as an approaching enemy craft or UFO.

Mars, with its distinctive red color, can be nearly as bright as Venus is when close to Earth, but normally it remains much less conspicuous. Jupiter is most often the second-brightest planet, approximately equaling in brilliance the brightest stars. Saturn is dimmer, and it varies considerably in brightness, depending on whether its large rings are seen nearly edge-on (faint) or more widely opened (bright).

Mercury is quite bright, but few people ever notice it because it never moves very far from the Sun (it's never more than 28° away in the sky) and is always seen against bright twilight skies.

True to their name, the planets "wander" against the background of the "fixed" stars. Although their apparent motions are complex, they reflect an underlying order upon which the heliocentric model of the solar system, as described in this chapter, was based. The positions of the planets are often listed in newspapers (sometimes on the weather page), and clear maps and guides to their locations can be found each month in such magazines as *Sky & Telescope* and *Astronomy* (available at most libraries and online). There are also a number of computer programs and phone and tablet apps that allow you to display where the planets are on any night.

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3.6: Key Terms

accelerate
to change velocity; to speed up, slow down, or change direction.

apparent magnitude
a measure of how bright a star looks in the sky; the larger the number, the dimmer the star appears to us

astrology
the pseudoscience that deals with the supposed influences on human destiny of the configurations and locations in the sky of the Sun, Moon, and planets

celestial equator
a great circle on the celestial sphere 90° from the celestial poles; where the celestial sphere intersects the plane of Earth's equator

celestial poles
points about which the celestial sphere appears to rotate; intersections of the celestial sphere with Earth's polar axis

celestial sphere
the apparent sphere of the sky; a sphere of large radius centered on the observer; directions of objects in the sky can be denoted by their position on the celestial sphere

circumpolar zone
those portions of the celestial sphere near the celestial poles that are either always above or always below the horizon

cosmology
the study of the organization and evolution of the universe

ecliptic
the apparent annual path of the Sun on the celestial sphere

epicycle
the circular orbit of a body in the Ptolemaic system, the center of which revolves about another circle (the deferent)

geocentric
centered on Earth

heliocentric
centered on the Sun

horizon (astronomical)
a great circle on the celestial sphere 90° from the zenith; more popularly, the circle around us where the dome of the sky meets Earth

horoscope
a chart used by astrologers that shows the positions along the zodiac and in the sky of the Sun, Moon, and planets at some given instant and as seen from a particular place on Earth—usually corresponding to the time and place of a person's birth

parallax
the apparent displacement of a nearby star that results from the motion of Earth around the Sun

planet

today, any of the larger objects revolving about the Sun or any similar objects that orbit other stars; in ancient times, any object that moved regularly among the fixed stars

precession (of Earth)

the slow, conical motion of Earth's axis of rotation caused principally by the gravitational pull of the Moon and Sun on Earth's equatorial bulge

retrograde motion

the apparent westward motion of a planet on the celestial sphere or with respect to the stars

year

the period of revolution of Earth around the Sun

zenith

the point on the celestial sphere opposite the direction of gravity; point directly above the observer

zodiac

a belt around the sky about 18° wide centered on the ecliptic

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3.7: Summary

2.1 The Sky Above

The direct evidence of our senses supports a geocentric perspective, with the celestial sphere pivoting on the celestial poles and rotating about a stationary Earth. We see only half of this sphere at one time, limited by the horizon; the point directly overhead is our zenith. The Sun's annual path on the celestial sphere is the ecliptic—a line that runs through the center of the zodiac, which is the 18-degree-wide strip of the sky within which we always find the Moon and planets. The celestial sphere is organized into 88 constellations, or sectors.

2.2 Ancient Astronomy

Ancient Greeks such as Aristotle recognized that Earth and the Moon are spheres, and understood the phases of the Moon, but because of their inability to detect stellar parallax, they rejected the idea that Earth moves. Eratosthenes measured the size of Earth with surprising precision. Hipparchus carried out many astronomical observations, making a star catalog, defining the system of stellar magnitudes, and discovering precession from the apparent shift in the position of the north celestial pole. Ptolemy of Alexandria summarized classic astronomy in his *Almagest*; he explained planetary motions, including retrograde motion, with remarkably good accuracy using a model centered on Earth. This geocentric model, based on combinations of uniform circular motion using epicycles, was accepted as authority for more than a thousand years.

2.3 Astrology and Astronomy

The ancient religion of astrology, with its main contribution to civilization a heightened interest in the heavens, began in Babylonia. It reached its peak in the Greco-Roman world, especially as recorded in the *Tetrabiblos* of Ptolemy. Natal astrology is based on the assumption that the positions of the planets at the time of our birth, as described by a horoscope, determine our future. However, modern tests clearly show that there is no evidence for this, even in a broad statistical sense, and there is no verifiable theory to explain what might cause such an astrological influence.

2.4 The Birth of Modern Astronomy

Nicolaus Copernicus introduced the heliocentric cosmology to Renaissance Europe in his book *De Revolutionibus*. Although he retained the Aristotelian idea of uniform circular motion, Copernicus suggested that Earth is a planet and that the planets all circle about the Sun, dethroning Earth from its position at the center of the universe. Galileo was the father of both modern experimental physics and telescopic astronomy. He studied the acceleration of moving objects and, in 1610, began telescopic observations, discovering the nature of the Milky Way, the large-scale features of the Moon, the phases of Venus, and four moons of Jupiter. Although he was accused of heresy for his support of heliocentric cosmology, Galileo is credited with observations and brilliant writings that convinced most of his scientific contemporaries of the reality of the Copernican theory.

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3.8: For Further Exploration

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Claudius Ptolemy: http://www-history.mcs.st-and.ac.uk/Biographies/Ptolemy.html. An interesting biography.

Hipparchus of Rhodes: http://www-history.mcs.st-andrews.ac.uk/Biographies/Hipparchus.html. An interesting biography.

Astronomy and Astrology

Astrology and Science: http://www.astrology-and-science.com/hpage.htm. The best site for a serious examination of the issues with astrology and the research on whether it works.

Real Romance in the Stars: www.independent.co.uk/voices/the-real-romance-in-the-stars-1527970.html. 1995 newspaper commentary attacking astrology.

Copernicus and Galileo

Galileo Galilei: http://www-history.mcs.st-andrews.ac.uk/Biographies/Galileo.html. A good biography with additional links.

Galileo Project: http://galileo.rice.edu/. Rice University’s repository of information on Galileo.

Nicolaus Copernicus: http://www-groups.dcs.st-and.ac.uk/~history/Biographies/Copernicus.html. A biography including links to photos about his life.

Videos

Astronomy and Astrology

Astrology Debunked: https://www.youtube.com/watch?v=y84HX2pMo5U. A compilation of scientists and magicians commenting skeptically on astrology (9:09).

Copernicus and Galileo

Galileo: http://www.biography.com/people/galileo-9305220. A brief biography (2:51).

Galileo’s Battle for the Heavens: https://www.youtube.com/playlist?list=PL28AF597A9C90E18E. A NOVA episode on PBS (1:48:55)

Nicolaus Copernicus: http://www.biography.com/people/nicolaus-copernicus-9256984. An overview of his life and work (2:41).

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3.9: Collaborative Group Activities

A. With your group, consider the question with which we began this chapter. How many ways can you think of to prove to a member of the “Flat Earth Society” that our planet is, indeed, round?

B. Make a list of ways in which a belief in astrology (the notion that your life path or personality is controlled by the position of the Sun, Moon, and planets at the time of your birth) might be harmful to an individual or to society at large.

C. Have members of the group compare their experiences with the night sky. Did you see the Milky Way? Can you identify any constellations? Make a list of reasons why you think so many fewer people know the night sky today than at the time of the ancient Greeks. Discuss reasons for why a person, today, may want to be acquainted with the night sky.

D. Constellations commemorate great heroes, dangers, or events in the legends of the people who name them. Suppose we had to start from scratch today, naming the patterns of stars in the sky. Whom or what would you choose to commemorate by naming a constellation after it, him, or her and why (begin with people from history; then if you have time, include living people as well)? Can the members of your group agree on any choices?

E. Although astronomical mythology no longer holds a powerful sway over the modern imagination, we still find proof of the power of astronomical images in the number of products in the marketplace that have astronomical names. How many can your group come up with? (Think of things like Milky Way candy bars, Eclipse and Orbit gum, or Comet cleanser.)

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CHAPTER OVERVIEW

3.10: Exercises

3.10.1: Review Questions

3.10.2: Thought Questions

3.10.3: Figuring for Yourself

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3.10.1: Review Questions

Review Questions

1.

From where on Earth could you observe all of the stars during the course of a year? What fraction of the sky can be seen from the North Pole?

2.

Give four ways to demonstrate that Earth is spherical.

3.

Explain, according to both geocentric and heliocentric cosmologies, why we see retrograde motion of the planets.

4.

In what ways did the work of Copernicus and Galileo differ from the views of the ancient Greeks and of their contemporaries?

5.

What were four of Galileo's discoveries that were important to astronomy?

6.

Explain the origin of the magnitude designation for determining the brightness of stars. Why does it seem to go backward, with smaller numbers indicating brighter stars?

7.

Ursa Minor contains the pole star, Polaris, and the asterism known as the Little Dipper. From most locations in the Northern Hemisphere, all of the stars in Ursa Minor are circumpolar. Does that mean these stars are also above the horizon during the day? Explain.

8.

How many degrees does the Sun move per day relative to the fixed stars? How many days does it take for the Sun to return to its original location relative to the fixed stars?

9.

How many degrees does the Moon move per day relative to the fixed stars? How many days does it take for the Moon to return to its original location relative to the fixed stars?

10.

Explain how the zodiacal constellations are different from the other constellations.

11.

The Sun was once thought to be a planet. Explain why.

12.

Is the ecliptic the same thing as the celestial equator? Explain.

13.

What is an asterism? Can you name an example?

14.

Why did Pythagoras believe that Earth should be spherical?

15.

How did Aristotle deduce that the Sun is farther away from Earth than the Moon?

16.

What are two ways in which Aristotle deduced that Earth is spherical?

17.

How did Hipparchus discover the wobble of Earth's axis, known as *precession*?

18.

Why did Ptolemy have to introduce multiple circles of motion for the planets instead of a single, simple circle to represent the planet's motion around the Earth?

19.

Why did Copernicus want to develop a completely new system for predicting planetary positions? Provide two reasons.

20.

What two factors made it difficult, at first, for astronomers to choose between the Copernican heliocentric model and the Ptolemaic geocentric model?

21.

What phases would Venus show if the geocentric model were correct?

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3.10.2: Thought Questions

Thought Questions

22.

Describe a practical way to determine in which constellation the Sun is found at any time of the year.

23.

What is a constellation as astronomers define it today? What does it mean when an astronomer says, “I saw a comet in Orion last night”?

24.

Draw a picture that explains why Venus goes through phases the way the Moon does, according to the heliocentric cosmology. Does Jupiter also go through phases as seen from Earth? Why?

25.

Show with a simple diagram how the lower parts of a ship disappear first as it sails away from you on a spherical Earth. Use the same diagram to show why lookouts on old sailing ships could see farther from the masthead than from the deck. Would there be any advantage to posting lookouts on the mast if Earth were flat? (Note that these nautical arguments for a spherical Earth were quite familiar to Columbus and other mariners of his time.)

26.

Parallaxes of stars were not observed by ancient astronomers. How can this fact be reconciled with the heliocentric hypothesis?

27.

Why do you think so many people still believe in astrology and spend money on it? What psychological needs does such a belief system satisfy?

28.

Consider three cosmological perspectives—the geocentric perspective, the heliocentric perspective, and the modern perspective—in which the Sun is a minor star on the outskirts of one galaxy among billions. Discuss some of the cultural and philosophical implications of each point of view.

29.

The north celestial pole appears at an altitude above the horizon that is equal to the observer’s latitude. Identify Polaris, the North Star, which lies very close to the north celestial pole. Measure its altitude. (This can be done with a protractor. Alternatively, your fist, extended at arm’s length, spans a distance approximately equal to 10°.) Compare this estimate with your latitude. (Note that this experiment cannot be performed easily in the Southern Hemisphere because Polaris itself is not visible in the south and no bright star is located near the south celestial pole.)

30.

What were two arguments or lines of evidence in support of the geocentric model?

31.

Although the Copernican system was largely correct to place the Sun at the center of all planetary motion, the model still gave inaccurate predictions for planetary positions. Explain the flaw in the Copernican model that hindered its accuracy.

32.

During a retrograde loop of Mars, would you expect Mars to be brighter than usual in the sky, about average in brightness, or fainter than usual in the sky? Explain.

33.

The Great Pyramid of Giza was constructed nearly 5000 years ago. Within the pyramid, archaeologists discovered a shaft leading from the central chamber out of the pyramid, oriented for favorable viewing of the bright star Thuban at that time. Thinking about Earth’s precession, explain why Thuban might have been an important star to the ancient Egyptians.

34.

Explain why more stars are circumpolar for observers at higher latitudes.

35.

What is the altitude of the north celestial pole in the sky from your latitude? If you do not know your latitude, look it up. If you are in the Southern Hemisphere, answer this question for the south celestial pole, since the north celestial pole is not visible from your location.

36.

If you were to drive to some city south of your current location, how would the altitude of the celestial pole in the sky change?

37.

Hipparchus could have warned us that the dates associated with each of the natal astrology sun signs would eventually be wrong. Explain why.

38.

Explain three lines of evidence that argue against the validity of astrology.

39.

What did Galileo discover about the planet Jupiter that cast doubt on exclusive geocentrism?

40.

What did Galileo discover about Venus that cast doubt on geocentrism?

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3.10.3: Figuring for Yourself

Figuring for Yourself

41.

Suppose Eratosthenes had found that, in Alexandria, at noon on the first day of summer, the line to the Sun makes an angle 30° with the vertical. What, then, would he have found for Earth's circumference?

42.

Suppose Eratosthenes' results for Earth's circumference were quite accurate. If the diameter of Earth is 12,740 km, what is the length of his stadium in kilometers?

43.

Suppose you are on a strange planet and observe, at night, that the stars do not rise and set, but circle parallel to the horizon. Next, you walk in a constant direction for 8000 miles, and at your new location on the planet, you find that all stars rise straight up in the east and set straight down in the west, perpendicular to the horizon. How could you determine the circumference of the planet without any further observations? What is the circumference, in miles, of the planet?

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CHAPTER OVERVIEW

4: Orbits and Gravity

How would you find a new planet at the outskirts of our solar system that is too dim to be seen with the unaided eye and is so far away that it moves very slowly among the stars? This was the problem confronting astronomers during the nineteenth century as they tried to pin down a full inventory of our solar system.

If we could look down on the solar system from somewhere out in space, interpreting planetary motions would be much simpler. But the fact is, we must observe the positions of all the other planets from our own moving planet. Scientists of the Renaissance did not know the details of Earth's motions any better than the motions of the other planets. Their problem, as we saw in Observing the Sky: The Birth of Astronomy, was that they had to deduce the nature of all planetary motion using only their earthbound observations of the other planets' positions in the sky. To solve this complex problem more fully, better observations and better models of the planetary system were needed.

4.1: Thinking Ahead
4.2: The Laws of Planetary Motion
4.3: Newton's Great Synthesis
4.4: Newton's Universal Law of Gravitation
4.5: Orbits in the Solar System
4.6: Motions of Satellites and Spacecraft
4.7: Gravity with More Than Two Bodies
4.8: Key Terms
4.9: Summary
4.10: For Further Exploration
4.11: Collaborative Group Activities
4.12: Exercises
4.12.1: Review Questions
4.12.2: Thought Questions
4.12.3: Figuring for Yourself

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4.1: Thinking Ahead



Figure 3.1 : International Space Station. This space habitat and laboratory orbits Earth once every 90 minutes. (credit: modification of work by NASA)

How would you find a new planet at the outskirts of our solar system that is too dim to be seen with the unaided eye and is so far away that it moves very slowly among the stars? This was the problem confronting astronomers during the nineteenth century as they tried to pin down a full inventory of our solar system.

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4.2: The Laws of Planetary Motion

Learning Objectives

By the end of this section, you will be able to:

- Describe how Tycho Brahe and Johannes Kepler contributed to our understanding of how planets move around the Sun
- Explain Kepler's three laws of planetary motion

At about the time that Galileo was beginning his experiments with falling bodies, the efforts of two other scientists dramatically advanced our understanding of the motions of the planets. These two astronomers were the observer Tycho Brahe and the mathematician Johannes Kepler. Together, they placed the speculations of Copernicus on a sound mathematical basis and paved the way for the work of Isaac Newton in the next century.

Tycho Brahe's Observatory

Three years after the publication of Copernicus' *De Revolutionibus*, Tycho Brahe was born to a family of Danish nobility. He developed an early interest in astronomy and, as a young man, made significant astronomical observations. Among these was a careful study of what we now know was an exploding star that flared up to great brilliance in the night sky. His growing reputation gained him the patronage of the Danish King Frederick II, and at the age of 30, Brahe was able to establish a fine astronomical observatory on the North Sea island of Hven (Figure 3.2). Brahe was the last and greatest of the pre-telescopic observers in Europe.



(a) (b)

Figure 3.2 : Tycho Brahe (1546–1601) and Johannes Kepler (1571–1630). (a) A stylized engraving shows Tycho Brahe using his instruments to measure the altitude of celestial objects above the horizon. The large curved instrument in the foreground allowed him to measure precise angles in the sky. Note that the scene includes hints of the grandeur of Brahe's observatory at Hven. (b) Kepler was a German mathematician and astronomer. His discovery of the basic laws that describe planetary motion placed the heliocentric cosmology of Copernicus on a firm mathematical basis.

At Hven, Brahe made a continuous record of the positions of the Sun, Moon, and planets for almost 20 years. His extensive and precise observations enabled him to note that the positions of the planets varied from those given in published tables, which were based on the work of Ptolemy. These data were extremely valuable, but Brahe didn't have the ability to analyze them and develop a better model than what Ptolemy had published. He was further inhibited because he was an extravagant and cantankerous fellow, and he accumulated enemies among government officials. When his patron, Frederick II, died in 1597, Brahe lost his political base and decided to leave Denmark. He took up residence in Prague, where he became court astronomer to Emperor Rudolf of Bohemia.

There, in the year before his death, Brahe found a most able young mathematician, Johannes Kepler, to assist him in analyzing his extensive planetary data.

Johannes Kepler

Johannes Kepler was born into a poor family in the German province of Württemberg and lived much of his life amid the turmoil of the Thirty Years' War (see Figure 3.2). He attended university at Tubingen and studied for a theological career. There, he learned the principles of the Copernican system and became converted to the heliocentric hypothesis. Eventually, Kepler went to Prague to serve as an assistant to Brahe, who set him to work trying to find a satisfactory theory of planetary motion—one that was compatible with the long series of observations made at Hven. Brahe was reluctant to provide Kepler with much material at any one time for fear that Kepler would discover the secrets of the universal motion by himself, thereby robbing Brahe of some of the glory. Only after Brahe's death in 1601 did Kepler get full possession of the priceless records. Their study occupied most of Kepler's time for more than 20 years.

Through his analysis of the motions of the planets, Kepler developed a series of principles, now known as *Kepler's three laws*, which described the behavior of planets based on their paths through space. The first two laws of planetary motion were published in 1609 in *The New Astronomy*. Their discovery was a profound step in the development of modern science.

The First Two Laws of Planetary Motion

The path of an object through space is called its orbit. Kepler initially assumed that the orbits of planets were circles, but doing so did not allow him to find orbits that were consistent with Brahe's observations. Working with the data for Mars, he eventually discovered that the orbit of that planet had the shape of a somewhat flattened circle, or ellipse. Next to the circle, the ellipse is the simplest kind of closed curve, belonging to a family of curves known as *conic sections* (Figure 3.3).

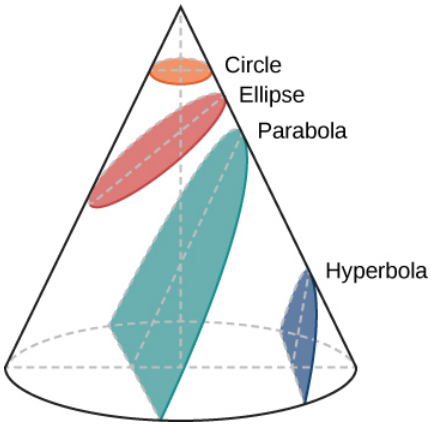


Figure 3.3 : Conic Sections. The circle, ellipse, parabola, and hyperbola are all formed by the intersection of a plane with a cone. This is why such curves are called conic sections.

You might recall from math classes that in a circle, the center is a special point. The distance from the center to anywhere on the circle is exactly the same. In an ellipse, the sum of the distance from two special points inside the ellipse to any point on the ellipse is always the same. These two points inside the ellipse are called its foci (singular: focus), a word invented for this purpose by Kepler.

This property suggests a simple way to draw an ellipse (Figure 3.4). We wrap the ends of a loop of string around two tacks pushed through a sheet of paper into a drawing board, so that the string is slack. If we push a pencil against the string, making the string taut, and then slide the pencil against the string all around the tacks, the curve that results is an ellipse. At any point where the pencil may be, the sum of the distances from the pencil to the two tacks is a constant length—the length of the string. The tacks are at the two foci of the ellipse.

The widest diameter of the ellipse is called its major axis. Half this distance—that is, the distance from the center of the ellipse to one end—is the semimajor axis, which is usually used to specify the size of the ellipse. For example, the semimajor axis of the orbit of Mars, which is also the planet's average distance from the Sun, is 228 million kilometers.

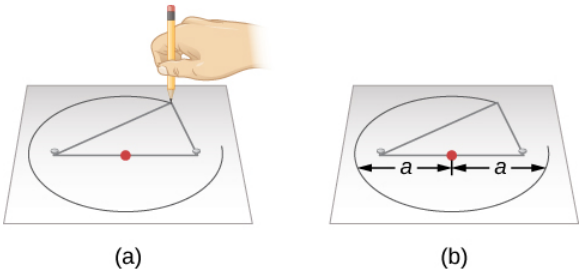


Figure 3.4 : Drawing an Ellipse. (a) We can construct an ellipse by pushing two tacks (the white objects) into a piece of paper on a drawing board, and then looping a string around the tacks. Each tack represents a focus of the ellipse, with one of the tacks being the Sun. Stretch the string tight using a pencil, and then move the pencil around the tacks. The length of the string remains the same, so that the sum of the distances from any point on the ellipse to the foci is always constant. (b) In this illustration, each semimajor axis is denoted by a. The distance $2a$ is called the major axis of the ellipse.

The shape (roundness) of an ellipse depends on how close together the two foci are, compared with the major axis. The ratio of the distance between the foci to the length of the major axis is called the eccentricity of the ellipse.

If the foci (or tacks) are moved to the same location, then the distance between the foci would be zero. This means that the eccentricity is zero and the ellipse is just a circle; thus, a circle can be called an ellipse of zero eccentricity. In a circle, the semimajor axis would be the radius.

Next, we can make ellipses of various elongations (or extended lengths) by varying the spacing of the tacks (as long as they are not farther apart than the length of the string). The greater the eccentricity, the more elongated is the ellipse, up to a maximum eccentricity of 1.0, when the ellipse becomes “flat,” the other extreme from a circle.

The size and shape of an ellipse are completely specified by its semimajor axis and its eccentricity. Using Brahe’s data, Kepler found that Mars has an elliptical orbit, with the Sun at one focus (the other focus is empty). The eccentricity of the orbit of Mars is only about 0.1; its orbit, drawn to scale, would be practically indistinguishable from a circle, but the difference turned out to be critical for understanding planetary motions.

Kepler generalized this result in his first law and said that *the orbits of all the planets are ellipses*. Here was a decisive moment in the history of human thought: it was not necessary to have only circles in order to have an acceptable cosmos. The universe could be a bit more complex than the Greek philosophers had wanted it to be.

Kepler’s second law deals with the speed with which each planet moves along its ellipse, also known as its orbital speed. Working with Brahe’s observations of Mars, Kepler discovered that the planet speeds up as it comes closer to the Sun and slows down as it pulls away from the Sun. He expressed the precise form of this relationship by imagining that the Sun and Mars are connected by a straight, elastic line. When Mars is closer to the Sun (positions 1 and 2 in Figure 3.5), the elastic line is not stretched as much, and the planet moves rapidly. Farther from the Sun, as in positions 3 and 4, the line is stretched a lot, and the planet does not move so fast. As Mars travels in its elliptical orbit around the Sun, the elastic line sweeps out areas of the ellipse as it moves (the colored regions in our figure). Kepler found that in equal intervals of time (t), the areas swept out in space by this imaginary line are always equal; that is, the area of the region B from 1 to 2 is the same as that of region A from 3 to 4.

If a planet moves in a circular orbit, the elastic line is always stretched the same amount and the planet moves at a constant speed around its orbit. But, as Kepler discovered, in most orbits that speed of a planet orbiting its star (or moon orbiting its planet) tends to vary because the orbit is elliptical.

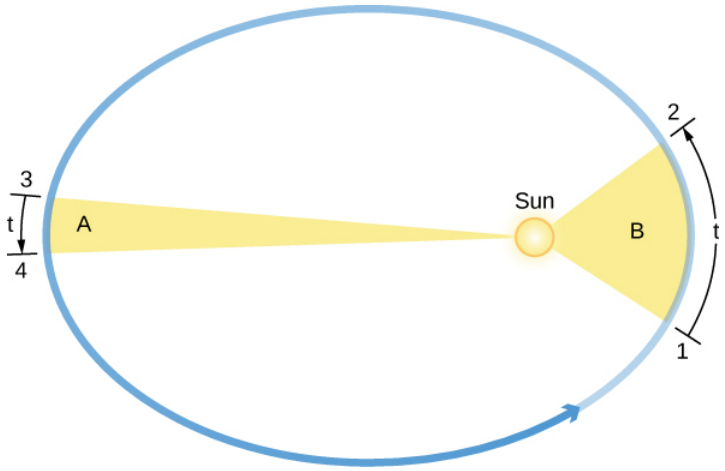


Figure 3.5 : Kepler's Second Law: The Law of Equal Areas. The orbital speed of a planet traveling around the Sun (the circular object inside the ellipse) varies in such a way that in equal intervals of time (t), a line between the Sun and a planet sweeps out equal areas (A and B). Note that the eccentricities of the planets' orbits in our solar system are substantially less than shown here.

Link to Learning

The Kepler's Second Law demonstrator from CCNY's ScienceSims project shows how an orbiting planet sweeps out the same area in the same time.

Kepler's Third Law

Kepler's first two laws of planetary motion describe the shape of a planet's orbit and allow us to calculate the speed of its motion at any point in the orbit. Kepler was pleased to have discovered such fundamental rules, but they did not satisfy his quest to fully understand planetary motions. He wanted to know why the orbits of the planets were spaced as they are and to find a mathematical pattern in their movements—a "harmony of the spheres" as he called it. For many years he worked to discover mathematical relationships governing planetary spacing and the time each planet took to go around the Sun.

In 1619, Kepler discovered a basic relationship to relate the planets' orbits to their relative distances from the Sun. We define a planet's orbital period, (***P***), as the time it takes a planet to travel once around the Sun. Also, recall that a planet's semimajor axis, *a*, is equal to its average distance from the Sun. The relationship, now known as *Kepler's third law*, says that a planet's orbital period squared is proportional to the semimajor axis of its orbit cubed, or

$$P^2 \propto a^3$$

When *P* (the orbital period) is measured in years, and *a* is expressed in a quantity known as an astronomical unit (AU), the two sides of the formula are not only proportional but equal. One AU is the average distance between Earth and the Sun and is approximately equal to 1.5×10^8 kilometers. In these units,

$$P^2 = a^3$$

Kepler's third law applies to all objects orbiting the Sun, including Earth, and provides a means for calculating their relative distances from the Sun from the time they take to orbit. Let's look at a specific example to illustrate how useful Kepler's third law is.

For instance, suppose you time how long Mars takes to go around the Sun (in Earth years). Kepler's third law can then be used to calculate Mars' average distance from the Sun. Mars' orbital period (1.88 Earth years) squared, or P^2, is $1.88^2 = 3.53$, and according to the equation for Kepler's third law, this equals the cube of its semimajor axis, or a^3. So what number must be cubed to

give 3.53? The answer is $1.52 (\text{since} 1.52 \times 1.52 \times 1.52 = 3.53)$. Thus, Mars' semimajor axis in astronomical units must be 1.52 AU. In other words, to go around the Sun in a little less than two years, Mars must be about 50% (half again) as far from the Sun as Earth is.

Example 3.1: Calculating Periods

Imagine an object is traveling around the Sun. What would be the orbital period of the object if its orbit has a semimajor axis of 50 AU?

Solution

From Kepler's third law, we know that (when we use units of years and AU)

$$P^2 = a^3$$

If the object's orbit has a semimajor axis of 50 AU (a = 50), we can cube 50 and then take the square root of the result to get P:

$$\begin{aligned} P &= \sqrt{a^3} \\ P &= \sqrt{50 \times 50 \times 50} = \sqrt{125{,}000} = 353.6 \text{ years} \end{aligned}$$

Therefore, the orbital period of the object is about 350 years. This would place our hypothetical object beyond the orbit of Pluto.

Exercise 4.2.1

What would be the orbital period of an asteroid (a rocky chunk between Mars and Jupiter) with a semimajor axis of 3 AU?

Answer

$P = \sqrt{3 \times 3 \times 3} = \sqrt{27} = 5.2$ years

Kepler's three laws of planetary motion can be summarized as follows:

- Kepler's first law: Each planet moves around the Sun in an orbit that is an ellipse, with the Sun at one focus of the ellipse.
- Kepler's second law: The straight line joining a planet and the Sun sweeps out equal areas in space in equal intervals of time.
- Kepler's third law: The square of a planet's orbital period is directly proportional to the cube of the semimajor axis of its orbit.

Kepler's three laws provide a precise geometric description of planetary motion within the framework of the Copernican system. With these tools, it was possible to calculate planetary positions with greatly improved precision. Still, Kepler's laws are purely descriptive: they do not help us understand what forces of nature constrain the planets to follow this particular set of rules. That step was left to Isaac Newton.

Example 3.2: Applying Kepler's Third Law

Using the orbital periods and semimajor axes for Venus and Earth that are provided here, calculate p^2 and a^3, and verify that they obey Kepler's third law. Venus' orbital period is 0.62 year, and its semimajor axis is 0.72 AU. Earth's orbital period is 1.00 year, and its semimajor axis is 1.00 AU.

Solution

We can use the equation for Kepler's third law, $P^2 \propto a^3$. For Venus, $P^2 = 0.62 \times 0.62 = 0.38$ and $a^3 = 0.72 \times 0.72 \times 0.72 = .037$ (rounding numbers sometimes causes minor discrepancies like this). The square of the orbital period (0.38) approximates the cube of the semimajor axis (0.37). Therefore, Venus obeys Kepler's third law. For Earth, $P^2 = 1.00 \times 1.00 = 1.00$ and $a^3 = 1.00 \times 1.00 \times 1.00 = 1.00$. The square of the orbital period (1.00) approximates (in this case, equals) the cube of the semimajor axis (1.00). Therefore, Earth obeys Kepler's third law.

Exercise 4.2.1

Using the orbital periods and semimajor axes for Saturn and Jupiter that are provided here, calculate P^2 and a^3, and verify that they obey Kepler's third law. Saturn's orbital period is 29.46 years, and its semimajor axis is 9.54 AU. Jupiter's orbital period is 11.86 years, and its semimajor axis is 5.20 AU.

Answer

For Saturn, $P^2 = 29.46 \times 29.46 = 867.9$and $a^3 = 9.54 \times 9.54 \times 9.54 = 868.3$ The square of the orbital period (867.9) approximates the cube of the semimajor axis (868.3). Therefore, Saturn obeys Kepler's third law.

Link to Learning

In honor of the scientist who first devised the laws that govern the motions of planets, the team that built the first spacecraft to search for planets orbiting other stars decided to name the probe "Kepler." Visit NASA's Kepler website to learn more about Johannes Kepler's life and his laws of planetary motion. NASA's Kepler website and follow the links that interest you.

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4.3: Newton's Great Synthesis

Learning Objectives

By the end of this section, you will be able to:

- Describe Newton's three laws of motion
- Explain how Newton's three laws of motion relate to momentum
- Define mass, volume, and density and how they differ
- Define angular momentum

It was the genius of Isaac Newton that found a conceptual framework that completely explained the observations and rules assembled by Galileo, Brahe, Kepler, and others. Newton was born in Lincolnshire, England, in the year after Galileo's death (Figure 3.6). Against the advice of his mother, who wanted him to stay home and help with the family farm, he entered Trinity College at Cambridge in 1661 and eight years later was appointed professor of mathematics. Among Newton's contemporaries in England were architect Christopher Wren, authors Aphra Behn and Daniel Defoe, and composer G. F. Handel.

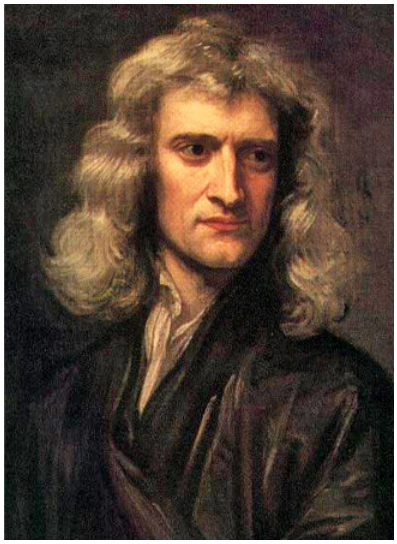


Figure 3.6 : Isaac Newton (1643–1727), 1689 Portrait by Sir Godfrey Kneller. Isaac Newton's work on the laws of motion, gravity, optics, and mathematics laid the foundations for much of physical science.

Newton's Laws of Motion

As a young man in college, Newton became interested in natural philosophy, as science was then called. He worked out some of his first ideas on machines and optics during the plague years of 1665 and 1666, when students were sent home from college. Newton, a moody and often difficult man, continued to work on his ideas in private, even inventing new mathematical tools to help him deal with the complexities involved. Eventually, his friend Edmund Halley (profiled in Comets and Asteroids: Debris of the Solar System) prevailed on him to collect and publish the results of his remarkable investigations on motion and gravity. The result was a volume that set out the underlying system of the physical world, *Philosophiae Naturalis Principia Mathematica*. The *Principia*, as the book is generally known, was published at Halley's expense in 1687.

At the very beginning of the *Principia*, Newton proposes three laws that would govern the motions of all objects:

- Newton's first law: Every object will continue to be in a state of rest or move at a constant speed in a straight line unless it is compelled to change by an outside force.
- Newton's second law: The change of motion of a body is proportional to and in the direction of the force acting on it.
- Newton's third law: For every action there is an equal and opposite reaction (*or:* the mutual actions of two bodies upon each other are always equal and act in opposite directions).

In the original Latin, the three laws contain only 59 words, but those few words set the stage for modern science. Let us examine them more carefully.

Interpretation of Newton's Laws

Newton's first law is a restatement of one of Galileo's discoveries, called the *conservation of momentum*. The law states that in the absence of any outside influence, there is a measure of a body's motion, called its momentum, that remains unchanged. You may have heard the term momentum used in everyday expressions, such as "This bill in Congress has a lot of momentum; it's going to be hard to stop."

Newton's first law is sometimes called the *law of inertia*, where inertia is the tendency of objects (and legislatures) to keep doing what they are already doing. In other words, a stationary object stays put, and a moving object keeps moving unless some force intervenes.

Let's define the precise meaning of momentum—it depends on three factors: (1) speed—how fast a body moves (zero if it is stationary), (2) the direction of its motion, and (3) its mass—a measure of the amount of matter in a body, which we will discuss later. Scientists use the term velocity to describe the speed and direction of motion. For example, 20 kilometers per hour due south is velocity, whereas 20 kilometers per hour just by itself is speed. Momentum then can be defined as an object's mass times its velocity.

It's not so easy to see this rule in action in the everyday world because of the many forces acting on a body at any one time. One important force is friction, which generally slows things down. If you roll a ball along the sidewalk, it eventually comes to a stop because the sidewalk exerts a rubbing force on the ball. But in the space between the stars, where there is so little matter that friction is insignificant, objects can in fact continue to move (to coast) indefinitely.

The momentum of a body can change only under the action of an outside influence. Newton's second law expresses *force* in terms of its ability to change momentum with time. A force (a push or a pull) has both size and direction. When a force is applied to a body, the momentum changes in the direction of the applied force. This means that a force is required to change either the speed or the direction of a body, or both—that is, to start it moving, to speed it up, to slow it down, to stop it, or to change its direction.

As you learned in Observing the Sky: The Birth of Astronomy, the rate of change in an object's velocity is called *acceleration*. Newton showed that the acceleration of a body was proportional to the force being applied to it. Suppose that after a long period of reading, you push an astronomy book away from you on a long, smooth table. (We use a smooth table so we can ignore friction.) If you push the book steadily, it will continue to speed up as long as you are pushing it. The harder you push the book, the larger its acceleration will be. How much a force will accelerate an object is also determined by the object's mass. If you kept pushing a pen with the same force with which you pushed the textbook, the pen—having less mass—would be accelerated to a greater speed.

Newton's third law is perhaps the most profound of the rules he discovered. Basically, it is a generalization of the first law, but it also gives us a way to define mass. If we consider a system of two or more objects isolated from outside influences, Newton's first law says that the total momentum of the objects should remain constant. Therefore, any change of momentum within the system must be balanced by another change that is equal and opposite so that the momentum of the entire system is not changed.

This means that forces in nature do not occur alone: we find that in each situation there is always a *pair* of forces that are equal to and opposite each other. If a force is exerted on an object, it must be exerted by something else, and the object will exert an equal and opposite force back on that something. We can look at a simple example to demonstrate this.

Suppose that a daredevil astronomy student—and avid skateboarder—wants to jump from his second-story dorm window onto his board below (we don't recommend trying this!). The force pulling him down after jumping (as we will see in the next section) is the force of gravity between him and Earth. Both he and Earth must experience the same total change of momentum because of the influence of these mutual forces. So, both the student and Earth are accelerated by each other's pull. However, the student does much more of the moving. Because Earth has enormously greater mass, it can experience the same change of momentum by accelerating only a very small amount. Things fall toward Earth all the time, but the acceleration of our planet as a result is far too small to be measured.

A more obvious example of the mutual nature of forces between objects is familiar to all who have batted a baseball. The recoil you feel as you swing your bat shows that the ball exerts a force on it during the impact, just as the bat does on the ball. Similarly, when a rifle you are bracing on your shoulder is discharged, the force pushing the bullet out of the muzzle is equal to the force pushing backward upon the gun and your shoulder.

This is the principle behind jet engines and rockets: the force that discharges the exhaust gases from the rear of the rocket is accompanied by the force that pushes the rocket forward. The exhaust gases need not push against air or Earth; a rocket actually operates best in a vacuum (Figure 3.7).



Figure 3.7 : Demonstrating Newton's Third Law. The U.S. Space Shuttle (here launching *Discovery*), powered by three fuel engines burning liquid oxygen and liquid hydrogen, with two solid fuel boosters, demonstrates Newton's third law. (credit: modification of work by NASA)

Link to Learning

For more about Isaac Newton's life and work, check out this timeline page with snapshots from his career, produced by the British Broadcasting Corporation (BBC).

Mass, Volume, and Density

Before we go on to discuss Newton's other work, we want to take a brief look at some terms that will be important to sort out clearly. We begin with mass, which is a measure of the amount of material within an object.

The *volume* of an object is the measure of the physical space it occupies. Volume is measured in cubic units, such as cubic centimeters or liters. The volume is the "size" of an object. A penny and an inflated balloon may both have the same mass, but they have very different volumes. The reason is that they also have very different *densities*, which is a measure of how much mass there is per unit volume. Specifically, density is the mass divided by the volume. Note that in everyday language we often use "heavy" and "light" as indications of density (rather than weight) as, for instance, when we say that iron is heavy or that whipped cream is light.

The units of density that will be used in this book are grams per cubic centimeter (g/cm^3).[1] If a block of some material has a mass of 300 grams and a volume of 100 cm^3, its density is 3 g/cm^3. Familiar materials span a considerable range in density, from artificial materials such as plastic insulating foam (less than 0.1 g/cm^3) to gold (19.3 g/cm^3). Table 3.1 gives the densities of some familiar materials. In the astronomical universe, much more remarkable densities can be found, all the way from a comet's tail (10^{-16} g/cm^3) to a collapsed "star corpse" called a neutron star (10^{15} g/cm^3).

Table 3.1: Densities of Common Materials

Material	Density (g/cm^3)
Gold	19.3
Lead	11.3
Iron	7.9
Earth (bulk)	5.5
Rock (typical)	2.5
Water	1
Wood (typical)	0.8
Insulating foam	0.1

Material	Density (g/cm^3)
Silica gel	0.02

To sum up, mass is *how much*, volume is *how big*, and density is *how tightly packed*.

Link to Learning

You can play with a simple animation demonstrating the relationship between the concepts of density, mass, and volume, and find out why objects like wood float in water.

Angular Momentum

A concept that is a bit more complex, but important for understanding many astronomical objects, is angular momentum, which is a measure of the rotation of a body as it revolves around some fixed point (an example is a planet orbiting the Sun). The angular momentum of an object is defined as the product of its mass, its velocity, and its distance from the fixed point around which it revolves.

If these three quantities remain constant—that is, if the motion of a particular object takes place at a constant velocity at a fixed distance from the spin center—then the angular momentum is also a constant. Kepler's second law is a consequence of the *conservation of angular momentum*. As a planet approaches the Sun on its elliptical orbit and the distance to the spin center decreases, the planet speeds up to conserve the angular momentum. Similarly, when the planet is farther from the Sun, it moves more slowly.

The conservation of angular momentum is illustrated by figure skaters, who bring their arms and legs in to spin more rapidly, and extend their arms and legs to slow down (Figure 3.8). You can duplicate this yourself on a well-oiled swivel stool by starting yourself spinning slowly with your arms extended and then pulling your arms in. Another example of the conservation of angular momentum is a shrinking cloud of dust or a star collapsing on itself (both are situations that you will learn about as you read on). As material moves to a lesser distance from the spin center, the speed of the material increases to conserve angular momentum.

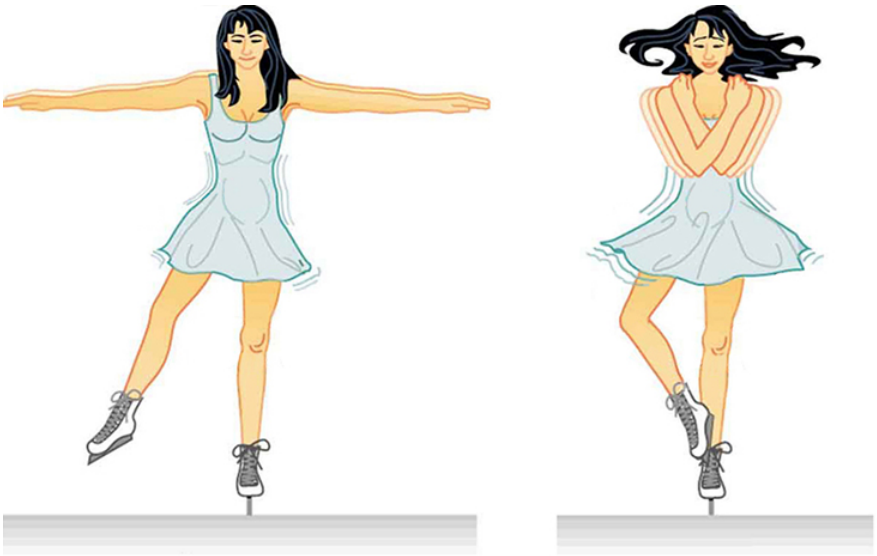


Figure 3.8 : Conservation of Angular Momentum. When a spinning figure skater brings in her arms, their distance from her spin center is smaller, so her speed increases. When her arms are out, their distance from the spin center is greater, so she slows down.

Footnotes

- 1Generally we use standard metric (or SI) units in this book. The proper metric unit of density in that system is kg/m^3. But to most people, g/cm^3 provides a more meaningful unit because the density of water is exactly 1 g/cm^3, and this is useful information for comparison. Density expressed in g/cm^3 is sometimes called specific density or specific weight.

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4.4: Newton's Universal Law of Gravitation

Learning Objectives

By the end of this section, you will be able to:

- Explain what determines the strength of gravity
- Describe how Newton's universal law of gravitation extends our understanding of Kepler's laws

Newton's laws of motion show that objects at rest will stay at rest and those in motion will continue moving uniformly in a straight line unless acted upon by a force. Thus, it is the *straight line* that defines the most natural state of motion. But the planets move in ellipses, not straight lines; therefore, some force must be bending their paths. That force, Newton proposed, was gravity.

In Newton's time, gravity was something associated with Earth alone. Everyday experience shows us that Earth exerts a gravitational force upon objects at its surface. If you drop something, it accelerates toward Earth as it falls. Newton's insight was that Earth's gravity might extend as far as the Moon and produce the force required to curve the Moon's path from a straight line and keep it in its orbit. He further hypothesized that gravity is not limited to Earth, but that there is a general force of attraction between all material bodies. If so, the attractive force between the Sun and each of the planets could keep them in their orbits. (This may seem part of our everyday thinking today, but it was a remarkable insight in Newton's time.)

Once Newton boldly hypothesized that there was a universal attraction among all bodies everywhere in space, he had to determine the exact nature of the attraction. The precise mathematical description of that gravitational force had to dictate that the planets move exactly as Kepler had described them to (as expressed in Kepler's three laws). Also, that gravitational force had to predict the correct behavior of falling bodies on Earth, as observed by Galileo. How must the force of gravity depend on distance in order for these conditions to be met?

The answer to this question required mathematical tools that had not yet been developed, but this did not deter Isaac Newton, who invented what we today call calculus to deal with this problem. Eventually he was able to conclude that the magnitude of the force of gravity must decrease with increasing distance between the Sun and a planet (or between any two objects) in proportion to the inverse square of their separation. In other words, if a planet were twice as far from the Sun, the force would be $\left(\frac{1}{2}\right)^2$, or $\frac{1}{4}$ as large. Put the planet three times farther away, and the force is $\left(\frac{1}{3}\right)^2$, or $\frac{1}{9}$ as large.

Newton also concluded that the gravitational attraction between two bodies must be proportional to their masses. The more mass an object has, the stronger the pull of its gravitational force. The gravitational attraction between any two objects is therefore given by one of the most famous equations in all of science:

$$F_{\text{gravity}} =$$

where F_{gravity} is the gravitational force between two objects, M_1 and M_2 are the masses of the two objects, and R is their separation. G is a constant number known as the *universal gravitational constant*, and the equation itself symbolically summarizes Newton's *universal law of gravitation*. With such a force and the laws of motion, Newton was able to show mathematically that the only orbits permitted were exactly those described by Kepler's laws.

Newton's universal law of gravitation works for the planets, but is it really universal? The gravitational theory should also predict the observed acceleration of the Moon toward Earth as it orbits Earth, as well as of any object (say, an apple) dropped near Earth's surface. The falling of an apple is something we can measure quite easily, but can we use it to predict the motions of the Moon?

Recall that according to Newton's second law, forces cause acceleration. Newton's universal law of gravitation says that the force acting upon (and therefore the acceleration of) an object toward Earth should be inversely proportional to the square of its distance from the center of Earth. Objects like apples at the surface of Earth, at a distance of one Earth-radius from the center of Earth, are observed to accelerate downward at 9.8 meters per second per second $(9.8\text{m}/\text{s}^2)$.

It is this force of gravity on the surface of Earth that gives us our sense of *weight*. Unlike your mass, which would remain the same on any planet or moon, your weight depends on the local force of gravity. So you would weigh less on Mars and the Moon than on Earth, even though there is no change in your mass. (Which means you would still have to go easy on the desserts in the college cafeteria when you got back!)

The Moon is 60 Earth radii away from the center of Earth. If gravity (and the acceleration it causes) gets weaker with distance squared, the acceleration the Moon experiences should be a lot less than for the apple. The acceleration should be $(1/60)^2 = 1/3600$ (or 3600 times less—about $0.00272 \mathrm{m/s^2}$). This is precisely the observed acceleration of the Moon in its orbit. (As we shall see, the Moon does not fall *to* Earth with this acceleration, but falls *around* Earth.) Imagine the thrill Newton must have felt to realize he had discovered, and verified, a law that holds for Earth, apples, the Moon, and, as far as he knew, everything in the universe.

Example 3.3: Calculating Weight

By what factor would a person's weight at the surface of Earth change if Earth had its present mass but eight times its present volume?

Solution

With eight times the volume, Earth's radius would double. This means the gravitational force at the surface would reduce by a factor of $\left(\frac{1}{2}\right)^2 = \frac{1}{4}$, so a person would weigh only one-fourth as much.

Exercise 4.4.1

By what factor would a person's weight at the surface of Earth change if Earth had its present size but only one-third its present mass?

Answer

With one-third its present mass, the gravitational force at the surface would reduce by a factor of $\frac{1}{3}$, so a person would weight only one-third as much.

Gravity is a "built-in" property of mass. Whenever there are masses in the universe, they will interact via the force of gravitational attraction. The more mass there is, the greater the force of attraction. Here on Earth, the largest concentration of mass is, of course, the planet we stand on, and its pull dominates the gravitational interactions we experience. But everything with mass attracts everything else with mass anywhere in the universe.

Newton's law also implies that gravity never becomes zero. It quickly gets weaker with distance, but it continues to act to some degree no matter how far away you get. The pull of the Sun is stronger at Mercury than at Pluto, but it can be felt far beyond Pluto, where astronomers have good evidence that it continuously makes enormous numbers of smaller icy bodies move around huge orbits. And the Sun's gravitational pull joins with the pull of billions of others stars to create the gravitational pull of our Milky Way Galaxy. That force, in turn, can make other smaller galaxies orbit around the Milky Way, and so on.

Why is it then, you may ask, that the astronauts aboard the Space Shuttle appear to have no gravitational forces acting on them when we see images on television of the astronauts and objects floating in the spacecraft? After all, the astronauts in the shuttle are only a few hundred kilometers above the surface of Earth, which is not a significant distance compared to the size of Earth, so gravity is certainly not a great deal weaker that much farther away. The astronauts feel "weightless" (meaning that they don't feel the gravitational force acting on them) for the same reason that passengers in an elevator whose cable has broken or in an airplane whose engines no longer work feel weightless: they are falling (Figure 3.9).[2]



Figure 3.9 : Astronauts in Free Fall. While in space, astronauts are falling freely, so they experience “weightlessness.” Clockwise from top left: Tracy Caldwell Dyson (NASA), Naoko Yamazaki (JAXA), Dorothy Metcalf-Lindenburger (NASA), and Stephanie Wilson (NASA). (credit: NASA)

When *falling*, they are in free fall and accelerate at the same rate as everything around them, including their spacecraft or a camera with which they are taking photographs of Earth. When doing so, astronauts experience no additional forces and therefore feel “weightless.” Unlike the falling elevator passengers, however, the astronauts are falling *around* Earth, not *to* Earth; as a result they will continue to fall and are said to be “in orbit” around Earth (see the next section for more about orbits).

Orbital Motion and Mass

Kepler’s laws describe the orbits of the objects whose motions are described by Newton’s laws of motion and the law of gravity. Knowing that gravity is the force that attracts planets toward the Sun, however, allowed Newton to rethink Kepler’s third law. Recall that Kepler had found a relationship between the orbital period of a planet’s revolution and its distance from the Sun. But Newton’s formulation introduces the additional factor of the masses of the Sun (M_1) and the planet (M_2), both expressed in units of the Sun’s mass. Newton’s universal law of gravitation can be used to show mathematically that this relationship is actually

$$a^3 = \left(M_1 + M_2\right) \times P^2$$

where a is the semimajor axis and P is the orbital period.

How did Kepler miss this factor? In units of the Sun’s mass, the mass of the Sun is 1, and in units of the Sun’s mass, the mass of a typical planet is a negligibly small factor. This means that the sum of the Sun’s mass and a planet’s mass, $\left(M_1 + M_2\right)$, is very, very

close to 1. This makes Newton's formula appear almost the same as Kepler's; the tiny mass of the planets compared to the Sun is the reason that Kepler did not realize that both masses had to be included in the calculation. There are many situations in astronomy, however, in which we *do* need to include the two mass terms—for example, when two stars or two galaxies orbit each other.

Including the mass term allows us to use this formula in a new way. If we can measure the motions (distances and orbital periods) of objects acting under their mutual gravity, then the formula will permit us to deduce their masses. For example, we can calculate the mass of the Sun by using the distances and orbital periods of the planets, or the mass of Jupiter by noting the motions of its moons.

Indeed, Newton's reformulation of Kepler's third law is one of the most powerful concepts in astronomy. Our ability to deduce the masses of objects from their motions is key to understanding the nature and evolution of many astronomical bodies. We will use this law repeatedly throughout this text in calculations that range from the orbits of comets to the interactions of galaxies.

Example 3.4: Calculating the Effects of Gravity

A planet like Earth is found orbiting its star at a distance of 1 AU in 0.71 Earth-year. Can you use Newton's version of Kepler's third law to find the mass of the star? (Remember that compared to the mass of a star, the mass of an earthlike planet can be considered negligible.)

Solution

In the formula $a^3 = (M_1 + M_2) \times P^2$, the factor $M_1 + M_2$ would now be approximately equal to M_1 (the mass of the star), since the planet's mass is so small by comparison. Then the formula becomes $a^3 = M_1 \times P^2$, and we can solve for M[1]:

$$M_1 = \frac{a^3}{P^2}$$

Since $a = 1, a^3 = 1$, so

$$M_1 = \frac{1}{P^2} = \frac{1}{0.71^2} = \frac{1}{0.5} = 2$$

So the mass of the star is twice the mass of our Sun. (Remember that this way of expressing the law has units in terms of Earth and the Sun, so masses are expressed in units of the mass of our Sun.)

Exercise 4.4.1

Suppose a star with twice the mass of our Sun had an earthlike planet that took 4 years to orbit the star. At what distance (semimajor axis) would this planet orbit its star?

Answer

Again, we can neglect the mass of the planet. So $M_1 = 2$ and $P = 4$ years. The formula is $a^3 = M_1 \times P^2$, so $a^3 = 2 \times 4^2 = 2 \times 16 = 32$. So a is the cube root of 32. To find this, you can just ask Google, "What is the cube root of 32?" and get the answer 3.2 AU.

Link to Learning

You might like to try a simulation that lets you move the Sun, Earth, Moon, and space station to see the effects of changing their distances on their gravitational forces and orbital paths. You can even turn off gravity and see what happens.

Footnotes

- 2In the film *Apollo 13*, the scenes in which the astronauts were "weightless" were actually filmed in a falling airplane. As you might imagine, the plane fell for only short periods before the engines engaged again.

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4.5: Orbits in the Solar System

Learning Objectives

By the end of this section, you will be able to:

- Compare the orbital characteristics of the planets in the solar system
- Compare the orbital characteristics of asteroids and comets in the solar system

Recall that the path of an object under the influence of gravity through space is called its orbit, whether that object is a spacecraft, planet, star, or galaxy. An orbit, once determined, allows the future positions of the object to be calculated.

Two points in any orbit in our solar system have been given special names. The place where the planet is closest to the Sun (*helios* in Greek) and moves the fastest is called the perihelion of its orbit, and the place where it is farthest away and moves the most slowly is the aphelion. For the Moon or a satellite orbiting Earth (*gee* in Greek), the corresponding terms are perigee and apogee. (In this book, we use the word *moon* for a natural object that goes around a planet and the word satellite to mean a human-made object that revolves around a planet.)

Orbits of the Planets

Today, Newton's work enables us to calculate and predict the orbits of the planets with marvelous precision. We know eight planets, beginning with Mercury closest to the Sun and extending outward to Neptune. The average orbital data for the planets are summarized in Table 3.2. (Ceres is the largest of the *asteroids*, now considered a dwarf planet.)

According to Kepler's laws, Mercury must have the shortest orbital period (88 Earth-days); thus, it has the highest orbital speed, averaging 48 kilometers per second. At the opposite extreme, Neptune has a period of 165 years and an average orbital speed of just 5 kilometers per second.

All the planets have orbits of rather low eccentricity. The most eccentric orbit is that of Mercury (0.21); the rest have eccentricities smaller than 0.1. It is fortunate that among the rest, Mars has an eccentricity greater than that of many of the other planets. Otherwise the pre-telescopic observations of Brahe would not have been sufficient for Kepler to deduce that its orbit had the shape of an ellipse rather than a circle.

The planetary orbits are also confined close to a common plane, which is near the plane of Earth's orbit (called the ecliptic). The strange orbit of the dwarf planet Pluto is inclined about 17° to the ecliptic, and that of the dwarf planet Eris (orbiting even farther away from the Sun than Pluto) by 44°, but all the major planets lie within 10° of the common plane of the solar system.

Link to Learning

JavaLab's solar system simulator allows you to explore the size and speed of the planets' orbits, and view the orbits from different perspectives.

Orbits of Asteroids and Comets

In addition to the eight planets, there are many smaller objects in the solar system. Some of these are moons (natural satellites) that orbit all the planets except Mercury and Venus. In addition, there are two classes of smaller objects in heliocentric orbits: *asteroids* and *comets*. Both asteroids and comets are believed to be small chunks of material left over from the formation process of the solar system.

In general, asteroids have orbits with smaller semimajor axes than do comets (Figure 3.10). The majority of them lie between 2.2 and 3.3 AU, in the region known as the asteroid belt (see Comets and Asteroids: Debris of the Solar System). As you can see in Table 3.2, the asteroid belt (represented by its largest member, Ceres) is in the middle of a gap between the orbits of Mars and Jupiter. It is because these two planets are so far apart that stable orbits of small bodies can exist in the region between them.

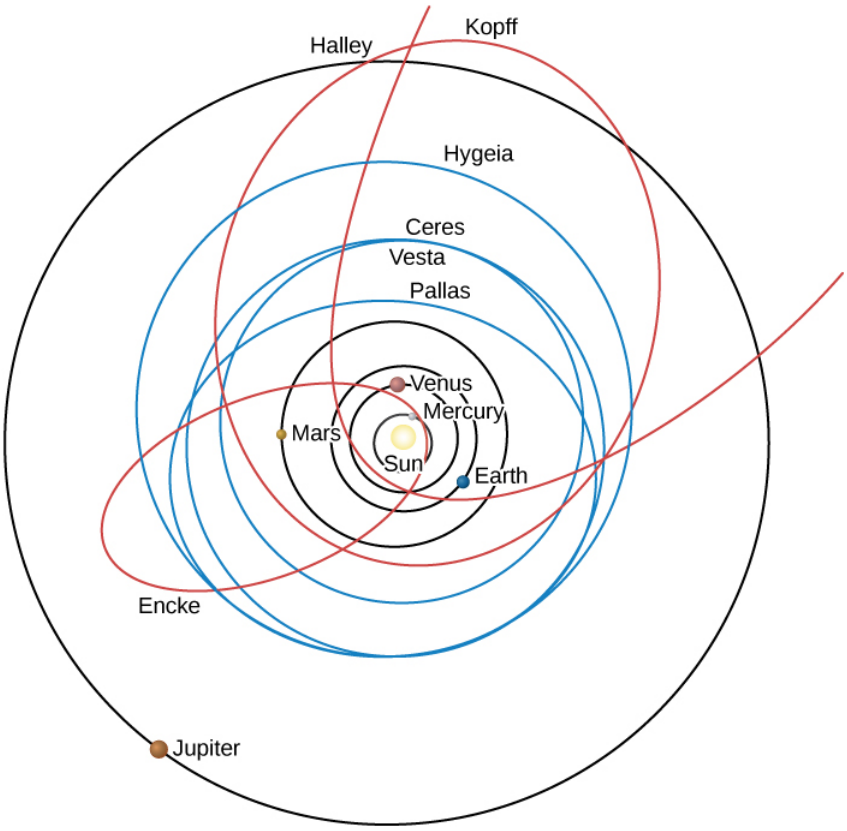


Figure 3.10 : Solar System Orbits. We see the orbits of typical comets and asteroids compared with those of the planets Mercury, Venus, Earth, Mars, and Jupiter (black circles). Shown in red are three comets: Halley, Kopff, and Encke. In blue are the four largest asteroids: Ceres, Pallas, Vesta, and Hygeia.

Table 3.2: Orbital Data for the Planets

Planet	Semimajor Axis (AU)	Period (y)	Eccentricity
Mercury	0.39	0.24	0.21
Venus	0.72	0.6	0.01
Earth	1	1.00	0.02
Mars	1.52	1.88	0.09
(Ceres)	2.77	4.6	0.08
Jupiter	5.20	11.86	0.05
Saturn	9.54	29.46	0.06
Uranus	19.19	84.01	0.05
Neptune	30.06	164.82	0.01

Comets generally have orbits of larger size and greater eccentricity than those of the asteroids. Typically, the eccentricity of their orbits is 0.8 or higher. According to Kepler's second law, therefore, they spend most of their time far from the Sun, moving very slowly. As they approach perihelion, the comets speed up and whip through the inner parts of their orbits more rapidly.

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4.6: Motions of Satellites and Spacecraft

Learning Objectives

By the end of this section, you will be able to:

- Explain how an object (such as a satellite) can be put into orbit around Earth
- Explain how an object (such as a planetary probe) can escape from orbit

Newton's universal law of gravitation and Kepler's laws describe the motions of Earth satellites and interplanetary spacecraft as well as the planets. Sputnik, the first artificial Earth satellite, was launched by what was then called the Soviet Union on October 4, 1957. Since that time, thousands of satellites have been placed into orbit around Earth, and spacecraft have also orbited the Moon, Venus, Mars, Jupiter, Saturn, and a number of asteroids and comets.

Once an artificial satellite is in orbit, its behavior is no different from that of a natural satellite, such as our Moon. If the satellite is high enough to be free of atmospheric friction, it will remain in orbit forever. However, although there is no difficulty in maintaining a satellite once it is in orbit, a great deal of energy is required to lift the spacecraft off Earth and accelerate it to orbital speed.

To illustrate how a satellite is launched, imagine a gun firing a bullet horizontally from the top of a high mountain, as in Figure 3.11, which has been adapted from a similar diagram by Newton. Imagine, further, that the friction of the air could be removed and that nothing gets in the bullet's way. Then the only force that acts on the bullet after it leaves the muzzle is the gravitational force between the bullet and Earth.

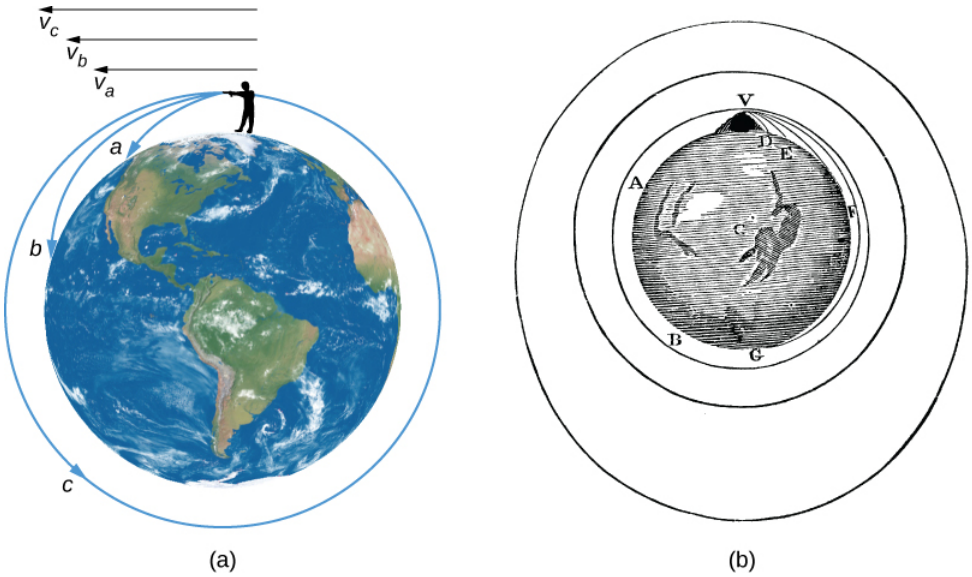


Figure 3.11 : Firing a Bullet into Orbit. (a) For paths *a* and *b*, the velocity is not enough to prevent gravity from pulling the bullet back to Earth; in case *c*, the velocity allows the bullet to fall completely around Earth. (b) This diagram by Newton in his *De Mundi Systemate*, 1731 edition, illustrates the same concept shown in (a).

If the bullet is fired with a velocity we can call v_a, the gravitational force acting upon it pulls it downward toward Earth, where it strikes the ground at point *a*. However, if it is given a higher muzzle velocity, v_b, its higher speed carries it farther before it hits the ground at point *b*.

If our bullet is given a high enough muzzle velocity, v_c, the curved surface of Earth causes the ground to remain the same distance from the bullet so that the bullet falls *around* Earth in a complete circle. The speed needed to do this—called the circular satellite velocity—is about 8 kilometers per second, or about 17,500 miles per hour in more familiar units.

Link to Learning

Use the Newton's Mountain simulator to see for yourself the effects of increasing an object's speed. You can raise the speed until you find the speed that is just fast enough for an object to orbit the Earth, the circular satellite velocity, and also the speed at which an object leaves the Earth forever, or the escape speed.

Each year, more than 50 new satellites are launched into orbit by such nations as Russia, the United States, China, Japan, India, and Israel, as well as by the European Space Agency (ESA), a consortium of European nations (Figure 3.12). Today, these satellites are used for weather tracking, ecology, global positioning systems, communications, and military purposes, to name a few uses. Most satellites are launched into low Earth orbit, since this requires the minimum launch energy. At the orbital speed of 8 kilometers per second, they circle the planet in about 90 minutes. Some of the very low Earth orbits are not indefinitely stable because, as Earth's atmosphere swells from time to time, a frictional drag is generated by the atmosphere on these satellites, eventually leading to a loss of energy and "decay" of the orbit.

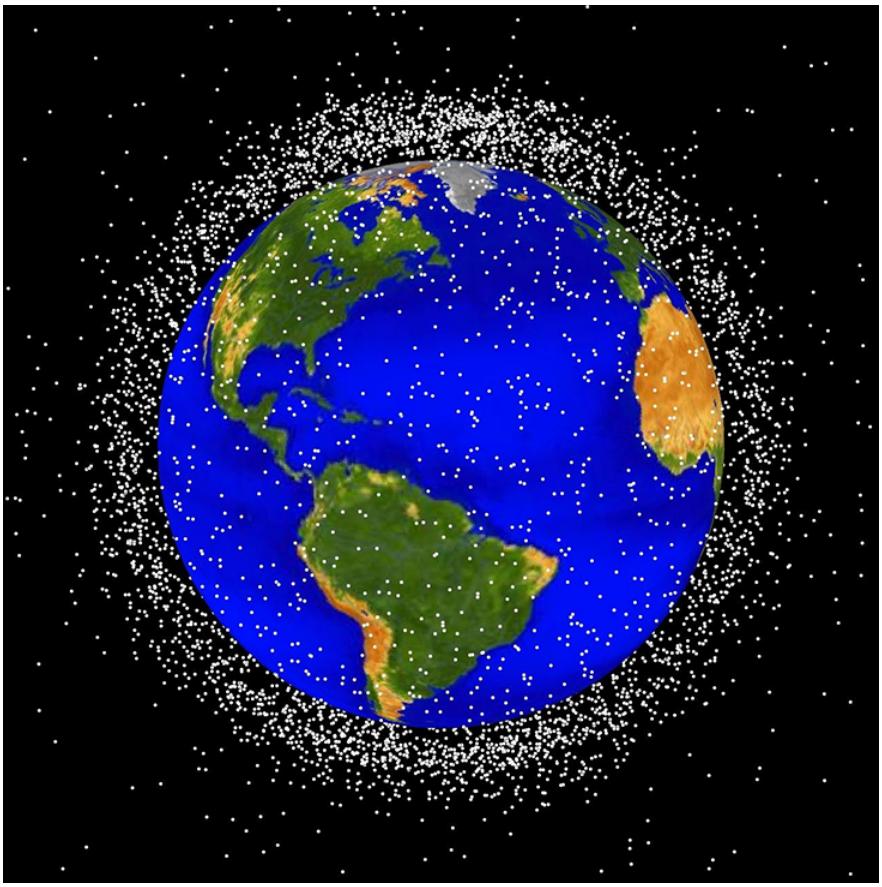


Figure 3.12 : Satellites in Earth Orbit. This figure shows the larger pieces of orbital debris that are being tracked by NASA in Earth's orbit. (credit: NASA/JSC)

Interplanetary Spacecraft

The exploration of the solar system has been carried out largely by robot spacecraft sent to the other planets. To escape Earth, these craft must achieve escape speed, the speed needed to move away from Earth forever, which is about 11 kilometers per second (about 25,000 miles per hour). After escaping Earth, these craft coast to their targets, subject only to minor trajectory adjustments provided by small thruster rockets on board. In interplanetary flight, these spacecraft follow orbits around the Sun that are modified only when they pass near one of the planets.

As it comes close to its target, a spacecraft is deflected by the planet's gravitational force into a modified orbit, either gaining or losing energy in the process. Spacecraft controllers have actually been able to use a planet's gravity to redirect a flyby spacecraft to a second target. For example, Voyager 2 used a series of gravity-assisted encounters to yield successive flybys of Jupiter (1979),

Saturn (1980), Uranus (1986), and Neptune (1989). The Galileo spacecraft, launched in 1989, flew past Venus once and Earth twice to gain the energy required to reach its ultimate goal of orbiting Jupiter.

If we wish to orbit a planet, we must slow the spacecraft with a rocket when the spacecraft is near its destination, allowing it to be captured into an elliptical orbit. Additional rocket thrust is required to bring a vehicle down from orbit for a landing on the surface. Finally, if a return trip to Earth is planned, the landed payload must include enough propulsive power to repeat the entire process in reverse.

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4.7: Gravity with More Than Two Bodies

Learning Objectives

By the end of this section, you will be able to:

- Explain how the gravitational interactions of many bodies can causes perturbations in their motions
- Explain how the planet Neptune was discovered

Until now, we have considered the Sun and a planet (or a planet and one of its moons) as nothing more than a pair of bodies revolving around each other. In fact, all the planets exert gravitational forces upon one another as well. These interplanetary attractions cause slight variations from the orbits than would be expected if the gravitational forces between planets were neglected. The motion of a body that is under the gravitational influence of two or more other bodies is very complicated and can be calculated properly only with large computers. Fortunately, astronomers have such computers at their disposal in universities and government research institutes.

The Interactions of Many Bodies

As an example, suppose you have a cluster of a thousand stars all orbiting a common center (such clusters are quite common, as we shall see in Star Clusters). If we know the exact position of each star at any given instant, we can calculate the combined gravitational force of the entire group on any one member of the cluster. Knowing the force on the star in question, we can therefore find how it will accelerate. If we know how it was moving to begin with, we can then calculate how it will move in the next instant of time, thus tracking its motion.

However, the problem is complicated by the fact that the other stars are also moving and thus changing the effect they will have on our star. Therefore, we must simultaneously calculate the acceleration of each star produced by the combination of the gravitational attractions of all the others in order to track the motions of all of them, and hence of any one. Such complex calculations have been carried out with modern computers to track the evolution of hypothetical clusters of stars with up to a million members (Figure 3.13).



Figure 3.13 : Modern Computing Power. These supercomputers at NASA's Ames Research Center are capable of tracking the motions of more than a million objects under their mutual gravitation. (credit: NASA Ames Research Center/Pleiades)

Within the solar system, the problem of computing the orbits of planets and spacecraft is somewhat simpler. We have seen that Kepler's laws, which do not take into account the gravitational effects of the other planets on an orbit, really work quite well. This is because these additional influences are very small in comparison with the dominant gravitational attraction of the Sun. Under such circumstances, it is possible to treat the effects of other bodies as small perturbations (or disturbances). During the eighteenth and nineteenth centuries, mathematicians developed many elegant techniques for calculating perturbations, permitting them to predict very precisely the positions of the planets. Such calculations eventually led to the prediction and discovery of a new planet in 1846.

The Discovery of Neptune

The discovery of the eighth planet, Neptune, was one of the high points in the development of gravitational theory. In 1781, William Herschel, a musician and amateur astronomer, accidentally discovered the seventh planet, Uranus. It happens that Uranus

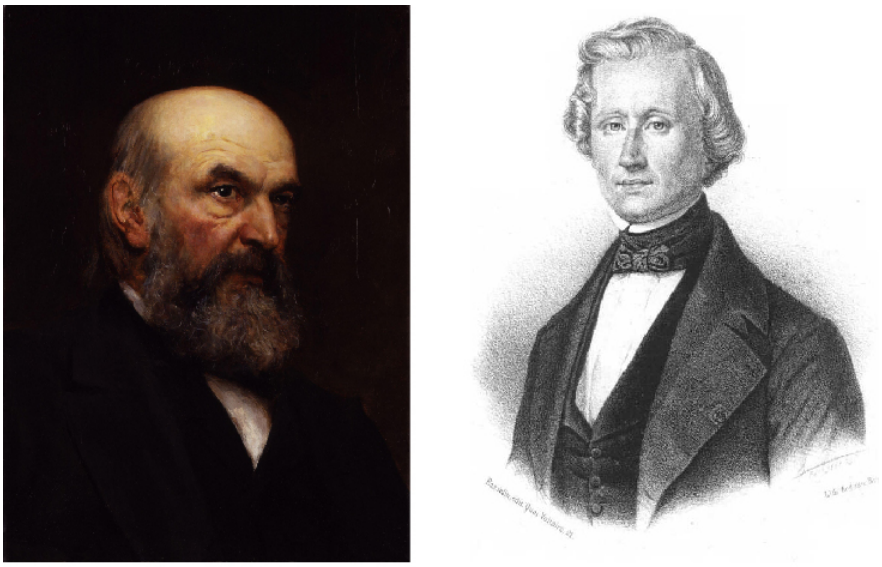
had been observed a century before, but in none of those earlier sightings was it recognized as a planet; rather, it was simply recorded as a star. Herschel's discovery showed that there could be planets in the solar system too dim to be visible to the unaided eye, but ready to be discovered with a telescope if we just knew where to look.

By 1790, an orbit had been calculated for Uranus using observations of its motion in the decade following its discovery. Even after allowance was made for the perturbing effects of Jupiter and Saturn, however, it was found that Uranus did not move on an orbit that exactly fit the earlier observations of it made since 1690. By 1840, the discrepancy between the positions observed for Uranus and those predicted from its computed orbit amounted to about 0.03°—an angle barely discernable to the unaided eye but still larger than the probable errors in the orbital calculations. In other words, Uranus just did not seem to move on the orbit predicted from Newtonian theory.

In 1843, John Couch Adams, a young Englishman who had just completed his studies at Cambridge, began a detailed mathematical analysis of the irregularities in the motion of Uranus to see whether they might be produced by the pull of an unknown planet. He hypothesized a planet more distant from the Sun than Uranus, and then determined the mass and orbit it had to have to account for the departures in Uranus' orbit. In October 1845, Adams delivered his results to George Airy, the British Astronomer Royal, informing him where in the sky to find the new planet. We now know that Adams' predicted position for the new body was correct to within 2°, but for a variety of reasons, Airy did not follow up right away.

Meanwhile, French mathematician Urbain Jean Joseph Le Verrier, unaware of Adams or his work, attacked the same problem and published its solution in June 1846. Airy, noting that Le Verrier's predicted position for the unknown planet agreed to within 1° with that of Adams, suggested to James Challis, Director of the Cambridge Observatory, that he begin a search for the new object. The Cambridge astronomer, having no up-to-date star charts of the Aquarius region of the sky where the planet was predicted to be, proceeded by recording the positions of all the faint stars he could observe with his telescope in that location. It was Challis' plan to repeat such plots at intervals of several days, in the hope that the planet would distinguish itself from a star by its motion. Unfortunately, he was negligent in examining his observations; although he had actually seen the planet, he did not recognize it.

About a month later, Le Verrier suggested to Johann Galle, an astronomer at the Berlin Observatory, that he look for the planet. Galle received Le Verrier's letter on September 23, 1846, and, possessing new charts of the Aquarius region, found and identified the planet that very night. It was less than a degree from the position Le Verrier predicted. The discovery of the eighth planet, now known as Neptune (the Latin name for the god of the sea), was a major triumph for gravitational theory for it dramatically confirmed the generality of Newton's laws. The honor for the discovery is properly shared by the two mathematicians, Adams and Le Verrier (Figure 3.14).



(a) (b)

Figure 3.14 : Mathematicians Who Discovered a Planet. (a) John Couch Adams (1819–1892) and (b) Urbain J. J. Le Verrier (1811–1877) share the credit for discovering the planet Neptune.

We should note that the discovery of Neptune was not a complete surprise to astronomers, who had long suspected the existence of the planet based on the "disobedient" motion of Uranus. On September 10, 1846, two weeks before Neptune was actually found,

John Herschel, son of the discoverer of Uranus, remarked in a speech before the British Association, “We see [the new planet] as Columbus saw America from the shores of Spain. Its movements have been felt trembling along the far-reaching line of our analysis with a certainty hardly inferior to ocular demonstration.”

This discovery was a major step forward in combining Newtonian theory with painstaking observations. Such work continues in our own times with the discovery of planets around other stars.

Link to Learning

For the fuller story of how Neptune was predicted and found (and the effect of the discovery on the search for Pluto), you can read this page on the mathematical discovery of planets.

Making Connections: Astronomy and the Poets

When Copernicus, Kepler, Galileo, and Newton formulated the fundamental rules that underlie everything in the physical world, they changed much more than the face of science. For some, they gave humanity the courage to let go of old superstitions and see the world as rational and manageable; for others, they upset comforting, ordered ways that had served humanity for centuries, leaving only a dry, “mechanical clockwork” universe in their wake.

Poets of the time reacted to such changes in their work and debated whether the new world picture was an appealing or frightening one. John Donne (1573–1631), in a poem called “Anatomy of the World,” laments the passing of the old certainties:

> *The new Philosophy [science] calls all in doubt,*
> *The element of fire is quite put out;*
> *The Sun is lost, and th’ earth, and no man’s wit*
> *Can well direct him where to look for it.*

(Here the “element of fire” refers also to the sphere of fire, which medieval thought placed between Earth and the Moon.)

By the next century, however, poets like Alexander Pope were celebrating Newton and the Newtonian world view. Pope’s famous couplet, written upon Newton’s death, goes

> *Nature, and nature’s laws lay hid in night.*
> *God said, Let Newton be! And all was light.*

In his 1733 poem, *An Essay on Man*, Pope delights in the complexity of the new views of the world, incomplete though they are:

> *Of man, what see we, but his station here,*
> *From which to reason, to which refer? . . .*
> *He, who thro’ vast immensity can pierce,*
> *See worlds on worlds compose one universe,*
> *Observe how system into system runs,*
> *What other planets circle other suns,*
> *What vary’d being peoples every star,*
> *May tell why Heav’n has made us as we are . . .*
> *All nature is but art, unknown to thee;*
> *All chance, direction, which thou canst not see;*
> *All discord, harmony not understood;*
> *All partial evil, universal good:*
> *And, in spite of pride, in erring reason’s spite,*
> *One truth is clear, whatever is, is right.*

Poets and philosophers continued to debate whether humanity was exalted or debased by the new views of science. The nineteenth-century poet Arthur Hugh Clough (1819–1861) cries out in his poem “The New Sinai”:

> *And as old from Sinai’s top God said that God is one,*
> *By science strict so speaks He now to tell us, there is None!*
> *Earth goes by chemic forces; Heaven’s a Mécanique Celeste!*
> *And heart and mind of humankind a watchwork as the rest!*

(A “mécanique celeste” is a clockwork model to demonstrate celestial motions.)

The twentieth-century poet Robinson Jeffers (whose brother was an astronomer) saw it differently in a poem called “Star Swirls”:

> *There is nothing like astronomy to pull the stuff out of man.*
> *His stupid dreams and red-rooster importance:*
> *Let him count the star-swirls.*

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4.8: Key Terms

angular momentum
the measure of the motion of a rotating object in terms of its speed and how widely the object's mass is distributed around its axis

aphelion
the point in its orbit where a planet (or other orbiting object) is farthest from the Sun

apogee
the point in its orbit where an Earth satellite is farthest from Earth

asteroid belt
the region of the solar system between the orbits of Mars and Jupiter in which most asteroids are located; the main belt, where the orbits are generally the most stable, extends from 2.2 to 3.3 AU from the Sun

astronomical unit (AU)
the unit of length defined as the average distance between Earth and the Sun; this distance is about 1.5×10^8 kilometers

density
the ratio of the mass of an object to its volume

eccentricity
in an ellipse, the ratio of the distance between the foci to the major axis

ellipse
a closed curve for which the sum of the distances from any point on the ellipse to two points inside (called the foci) is always the same

escape speed
the speed a body must achieve to break away from the gravity of another body

focus
(plural: foci) one of two fixed points inside an ellipse from which the sum of the distances to any point on the ellipse is constant

gravity
the mutual attraction of material bodies or particles

Kepler's first law
each planet moves around the Sun in an orbit that is an ellipse, with the Sun at one focus of the ellipse

Kepler's second law
the straight line joining a planet and the Sun sweeps out equal areas in space in equal intervals of time

Kepler's third law
the square of a planet's orbital period is directly proportional to the cube of the semimajor axis of its orbit

major axis
the maximum diameter of an ellipse

mass
a measure of the amount of material within an object

momentum

the measure of the amount of motion of a body; the momentum of a body is the product of its mass and velocity; in the absence of an unbalanced force, momentum is conserved

Newton's first law
every object will continue to be in a state of rest or move at a constant speed in a straight line unless it is compelled to change by an outside force

Newton's second law
the change of motion of a body is proportional to and in the direction of the force acting on it

Newton's third law
for every action there is an equal and opposite reaction (*or:* the mutual actions of two bodies upon each other are always equal and act in opposite directions)

orbit
the path of an object that is in revolution about another object or point

orbital period (*P*)
the time it takes an object to travel once around the Sun

orbital speed
the speed at which an object (usually a planet) orbits around the mass of another object; in the case of a planet, the speed at which each planet moves along its ellipse

perigee
the point in its orbit where an Earth satellite is closest to Earth

perihelion
the point in its orbit where a planet (or other orbiting object) is nearest to the Sun

perturbation
a small disturbing effect on the motion or orbit of a body produced by a third body

satellite
an object that revolves around a planet

semimajor axis
half of the major axis of a conic section, such as an ellipse

velocity
the speed and direction a body is moving—for example, 44 kilometers per second toward the north galactic pole

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4.9: Summary

3.1 The Laws of Planetary Motion

Tycho Brahe's accurate observations of planetary positions provided the data used by Johannes Kepler to derive his three fundamental laws of planetary motion. Kepler's laws describe the behavior of planets in their orbits as follows: (1) planetary orbits are ellipses with the Sun at one focus; (2) in equal intervals, a planet's orbit sweeps out equal areas; and (3) the relationship between the orbital period (P) and the semimajor axis (a) of an orbit is given by $P^2 = a^3$ (when a is in units of AU and P is in units of Earth years).

3.2 Newton's Great Synthesis

In his *Principia*, Isaac Newton established the three laws that govern the motion of objects: (1) objects continue to be at rest or move with a constant velocity unless acted upon by an outside force; (2) an outside force causes an acceleration (and changes the momentum) for an object; and (3) for every action there is an equal and opposite reaction. Momentum is a measure of the motion of an object and depends on both its mass and its velocity. Angular momentum is a measure of the motion of a spinning or revolving object and depends on its mass, velocity, and distance from the point around which it revolves. The density of an object is its mass divided by its volume.

3.3 Newton's Universal Law of Gravitation

Gravity, the attractive force between all masses, is what keeps the planets in orbit. Newton's universal law of gravitation relates the gravitational force to mass and distance:

$$F_{\text{gravity}} =$$

The force of gravity is what gives us our sense of weight. Unlike mass, which is constant, weight can vary depending on the force of gravity (or acceleration) you feel. When Kepler's laws are reexamined in the light of Newton's gravitational law, it becomes clear that the masses of both objects are important for the third law, which becomes $a^3 = (M_1 + M_2) \times P^2$. Mutual gravitational effects permit us to calculate the masses of astronomical objects, from comets to galaxies.

3.4 Orbits in the Solar System

The closest point in a satellite orbit around Earth is its perigee, and the farthest point is its apogee (corresponding to perihelion and aphelion for an orbit around the Sun). The planets follow orbits around the Sun that are nearly circular and in the same plane. Most asteroids are found between Mars and Jupiter in the asteroid belt, whereas comets generally follow orbits of high eccentricity.

3.5 Motions of Satellites and Spacecraft

The orbit of an artificial satellite depends on the circumstances of its launch. The circular satellite velocity needed to orbit Earth's surface is 8 kilometers per second, and the escape speed from our planet is 11 kilometers per second. There are many possible interplanetary trajectories, including those that use gravity-assisted flybys of one object to redirect the spacecraft toward its next target.

3.6 Gravity with More Than Two Bodies

Calculating the gravitational interaction of more than two objects is complicated and requires large computers. If one object (like the Sun in our solar system) dominates gravitationally, it is possible to calculate the effects of a second object in terms of small perturbations. This approach was used by John Couch Adams and Urbain Le Verrier to predict the position of Neptune from its perturbations of the orbit of Uranus and thus discover a new planet mathematically.

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4.10: For Further Exploration

Articles

Brahe and Kepler

Christianson, G. “The Celestial Palace of Tycho Brahe.” *Scientific American* (February 1961): 118.

Gingerich, O. “Johannes Kepler and the Rudolphine Tables.” *Sky & Telescope* (December 1971): 328. Brief article on Kepler’s work.

Wilson, C. “How Did Kepler Discover His First Two Laws?” *Scientific American* (March 1972): 92.

Newton

Christianson, G. “Newton’s *Principia*: A Retrospective.” *Sky & Telescope* (July 1987): 18.

Cohen, I. “Newton’s Discovery of Gravity.” *Scientific American* (March 1981): 166.

Gingerich, O. “Newton, Halley, and the Comet.” *Sky & Telescope* (March 1986): 230.

Sullivant, R. “When the Apple Falls.” *Astronomy* (April 1998): 55. Brief overview.

The Discovery of Neptune

Sheehan, W., et al. “The Case of the Pilfered Planet: Did the British Steal Neptune?” *Scientific American* (December 2004): 92.

Websites

Brahe and Kepler

Johannes Kepler: http://www.britannica.com/biography/Johannes-Kepler. Encyclopedia Britannica article.

Johannes Kepler: http://www-history.mcs.st-andrews.ac.uk/Biographies/Kepler.html. MacTutor article with additional links.

Noble Dane: Images of Tycho Brahe: http://www.mhs.ox.ac.uk/tycho/index.htm. A virtual museum exhibit from Oxford.

Newton

Sir Isaac Newton: http://www-groups.dcs.st-and.ac.uk/~history//Biographies/Newton.html. MacTutor article with additional links.

Sir Isaac Newton: http://www.luminarium.org/sevenlit/newton/newtonbio.htm. Newton Biography at the Luminarium.

The Discovery of Neptune

Adams, Airy, and the Discovery of Neptune: http://www.mikeoates.org/lassell/adams-airy.htm. A defense of Airy’s role by historian Alan Chapman.

Mathematical Discovery of Planets: www-groups.dcs.st-and.ac.uk/~history/HistTopics/Neptune_and_Pluto.html. MacTutor article.

Videos

Brahe and Kepler

“Harmony of the Worlds.” This third episode of Carl Sagan’s TV series *Cosmos* focuses on Kepler and his life and work.

Tycho Brahe, Johannes Kepler, and Planetary Motion: https://www.youtube.com/watch?v=x3ALuycrCwI. German-produced video, in English (14:27).

Newton

Beyond the Big Bang: Sir Isaac Newton’s Law of Gravity: http://www.history.com/topics/enlightenment/videos/beyond-the-big-bang-sir-isaac-newtons-law-of-gravity. From the History Channel (4:35).

Sir Isaac Newton versus Bill Nye: Epic Rap Battles of History: https://www.youtube.com/watch?v=8yis7GzlXNM. (2:47).

The Discovery of Neptune

Richard Feynman: On the Discovery of Neptune: https://www.youtube.com/watch?v=FgXQffVgZRs. A brief black-and-white Caltech lecture (4:33).

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4.11: Collaborative Group Activities

A. An eccentric, but very rich, alumnus of your college makes a bet with the dean that if you drop a baseball and a bowling ball from the tallest building on campus, the bowling ball would hit the ground first. Have your group discuss whether you would make a side bet that the alumnus is right. How would you decide who is right?
B. Suppose someone in your astronomy class was unhappy about his or her weight. Where could a person go to weigh one-fourth as much as he or she does now? Would changing the unhappy person's weight have any effect on his or her mass?
C. When the Apollo astronauts landed on the Moon, some commentators commented that it ruined the mystery and "poetry" of the Moon forever (and that lovers could never gaze at the full moon in the same way again). Others felt that knowing more about the Moon could only enhance its interest to us as we see it from Earth. How do the various members of your group feel? Why?
D. Figure 3.12 shows a swarm of satellites in orbit around Earth. What do you think all these satellites do? How many categories of functions for Earth satellites can your group come up with?
E. The Making Connections feature box Astronomy and the Poets discusses how poets included the most recent astronomical knowledge in their poetry. Is this still happening today? Can your group members come up with any poems or songs that you know that deal with astronomy or outer space? If not, perhaps you could find some online, or by asking friends or roommates who are into poetry or music.

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CHAPTER OVERVIEW

4.12: Exercises

4.12.1: Review Questions

4.12.2: Thought Questions

4.12.3: Figuring for Yourself

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4.12.1: Review Questions

Review Questions

1.

State Kepler’s three laws in your own words.

2.

Why did Kepler need Tycho Brahe’s data to formulate his laws?

3.

Which has more mass: an armful of feathers or an armful of lead? Which has more volume: a kilogram of feathers or a kilogram of lead? Which has higher density: a kilogram of feathers or a kilogram of lead?

4.

Explain how Kepler was able to find a relationship (his third law) between the orbital periods and distances of the planets that did not depend on the masses of the planets or the Sun.

5.

Write out Newton’s three laws of motion in terms of what happens with the momentum of objects.

6.

Which major planet has the largest . . .

A. semimajor axis?
B. average orbital speed around the Sun?
C. orbital period around the Sun?
D. eccentricity?

7.

Why do we say that Neptune was the first planet to be discovered through the use of mathematics?

8.

Why was Brahe reluctant to provide Kepler with all his data at one time?

9.

According to Kepler’s second law, where in a planet’s orbit would it be moving fastest? Where would it be moving slowest?

10.

The gas pedal, the brakes, and the steering wheel all have the ability to accelerate a car—how?

11.

Explain how a rocket can propel itself using Newton’s third law.

12.

A certain material has a mass of 565 g while occupying Unexpected text node: 'Table 3.1.)'

13.

To calculate the momentum of an object, which properties of an object do you need to know?

14.

To calculate the angular momentum of an object, which properties of an object do you need to know?

15.

What was the great insight Newton had regarding Earth’s gravity that allowed him to develop the universal law of gravitation?

16.

Which of these properties of an object best quantifies its inertia: velocity, acceleration, volume, mass, or temperature?

17.

Pluto’s orbit is more eccentric than any of the major planets. What does that mean?

18.

Why is Tycho Brahe often called “the greatest naked-eye astronomer” of all time?

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4.12.2: Thought Questions

Thought Questions

19.

Is it possible to escape the force of gravity by going into orbit around Earth? How does the force of gravity in the International Space Station (orbiting an average of 400 km above Earth's surface) compare with that on the ground?

20.

What is the momentum of an object whose velocity is zero? How does Newton's first law of motion include the case of an object at rest?

21.

Evil space aliens drop you and your fellow astronomy student 1 km apart out in space, very far from any star or planet. Discuss the effects of gravity on each of you.

22.

A body moves in a perfectly circular path at constant speed. Are there forces acting in such a system? How do you know?

23.

As friction with our atmosphere causes a satellite to spiral inward, closer to Earth, its orbital speed increases. Why?

24.

Use a history book, an encyclopedia, or the internet to find out what else was happening in England during Newton's lifetime and discuss what trends of the time might have contributed to his accomplishments and the rapid acceptance of his work.

25.

Two asteroids begin to gravitationally attract one another. If one asteroid has twice the mass of the other, which one experiences the greater force? Which one experiences the greater acceleration?

26.

How does the mass of an astronaut change when she travels from Earth to the Moon? How does her weight change?

27.

If there is gravity where the International Space Station (ISS) is located above Earth, why doesn't the space station get pulled back down to Earth?

28.

Compare the density, weight, mass, and volume of a pound of gold to a pound of iron on the surface of Earth.

29.

If identical spacecraft were orbiting Mars and Earth at identical radii (distances), which spacecraft would be moving faster? Why?

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4.12.3: Figuring for Yourself

Figuring for Yourself

30.

By what factor would a person’s weight be increased if Earth had 10 times its present mass, but the same volume?

31.

Suppose astronomers find an earthlike planet that is twice the size of Earth (that is, its radius is twice that of Earth’s). What must be the mass of this planet such that the gravitational force (F_{gravity}) at the surface would be identical to Earth’s?

32.

What is the semimajor axis of a circle of diameter 24 cm? What is its eccentricity?

33.

If 24 g of material fills a cube 2 cm on a side, what is the density of the material?

34.

If 128 g of material is in the shape of a brick 2 cm wide, 4 cm high, and 8 cm long, what is the density of the material?

35.

If the major axis of an ellipse is 16 cm, what is the semimajor axis? If the eccentricity is 0.8, would this ellipse be best described as mostly circular or very elongated?

36.

What is the average distance from the Sun (in astronomical units) of an asteroid with an orbital period of 8 years?

37.

What is the average distance from the Sun (in astronomical units) of a planet with an orbital period of 45.66 years?

38.

In 1996, astronomers discovered an icy object beyond Pluto that was given the designation 1996 TL 66. It has a semimajor axis of 84 AU. What is its orbital period according to Kepler’s third law?

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CHAPTER OVERVIEW

5: Radiation and Spectra

The nearest star is so far away that the fastest spacecraft humans have built would take almost 100,000 years to get there. Yet we very much want to know what material this neighbor star is composed of and how it differs from our own Sun. How can we learn about the chemical makeup of stars that we cannot hope to visit or sample?

In astronomy, most of the objects that we study are completely beyond our reach. The temperature of the Sun is so high that a spacecraft would be fried long before it reached it, and the stars are much too far away to visit in our lifetimes with the technology now available. Even light, which travels at a speed of 300,000 kilometers per second (km/s), takes more than 4 years to reach us from the nearest star. If we want to learn about the Sun and stars, we must rely on techniques that allow us to analyze them from a distance.

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5.1: Thinking Ahead

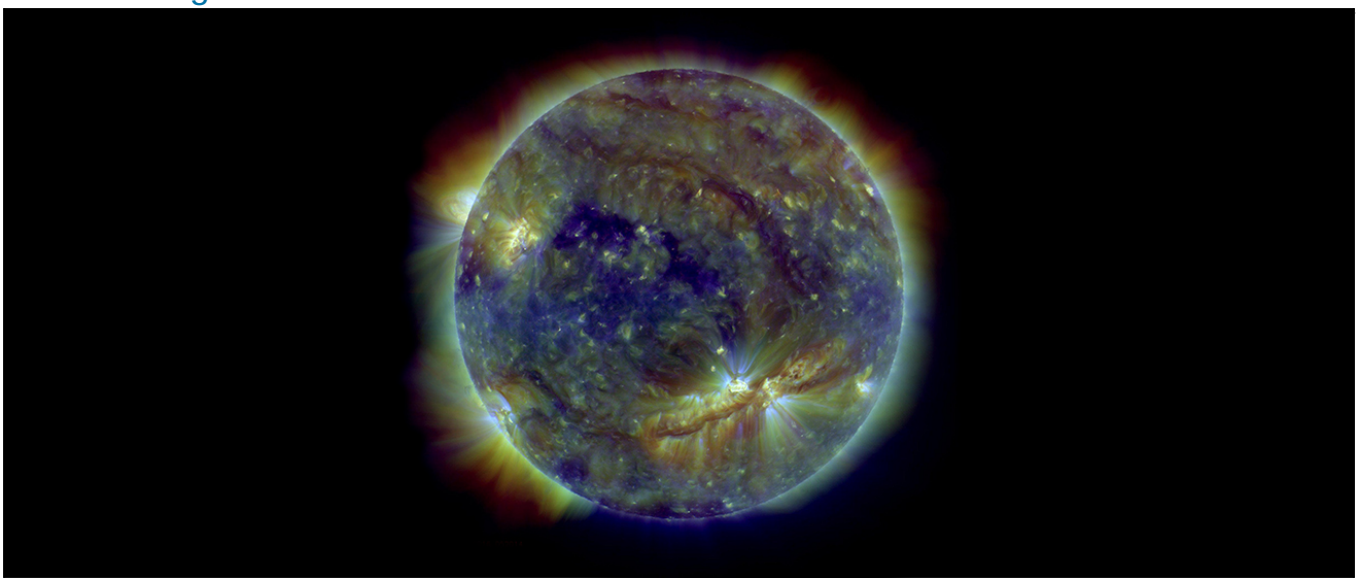


Figure 5.1 : Our Sun in Ultraviolet Light. This photograph of the Sun was taken at several different wavelengths of ultraviolet, which our eyes cannot see, and then color coded so it reveals activity in our Sun's atmosphere that cannot be observed in visible light. This is why it is important to observe the Sun and other astronomical objects in wavelengths other than the visible band of the spectrum. This image was taken by a satellite from above Earth's atmosphere, which is necessary since Earth's atmosphere absorbs much of the ultraviolet light coming from space. (credit: modification of work by NASA)

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5.2: The Behavior of Light

Learning Objectives

By the end of this section, you will be able to:

- Explain the evidence for Maxwell's electromagnetic model of light
- Describe the relationship between wavelength, frequency, and speed of light
- Discuss the particle model of light and the definition of photon
- Explain how and why the amount of light we see from an object depends upon its distance

Coded into the light and other kinds of radiation that reach us from objects in the universe is a wide range of information about what those objects are like and how they work. If we can decipher this code and read the messages it contains, we can learn an enormous amount about the cosmos without ever having to leave Earth or its immediate environment.

The visible light and other radiation we receive from the stars and planets is generated by processes at the atomic level—by changes in the way the parts of an atom interact and move. Thus, to appreciate how light is generated, we must explore how atoms work. There is a bit of irony in the fact that in order to understand some of the largest structures in the universe, we must become acquainted with some of the smallest.

Notice that we have twice used the phrase "light and other radiation." One of the key ideas explored in this chapter is that visible light is not unique; it is merely the most familiar example of a much larger family of radiation that can carry information to us.

The word "radiation" will be used frequently in this book, so it is important to understand what it means. In everyday language, "radiation" is often used to describe certain kinds of energetic subatomic particles released by radioactive materials in our environment. (An example is the kind of radiation used to treat some cancers.) But this is not what we mean when we use the word "radiation" in an astronomy text. *Radiation*, as used in this book, is a general term for waves (including light waves) that *radiate* outward from a source.

As we saw in Orbits and Gravity, Newton's theory of gravity accounts for the motions of planets as well as objects on Earth. Application of this theory to a variety of problems dominated the work of scientists for nearly two centuries. In the nineteenth century, many physicists turned to the study of electricity and magnetism, which are intimately connected with the production of light.

The scientist who played a role in this field comparable to Newton's role in the study of gravity was physicist James Clerk Maxwell, born and educated in Scotland (Figure 5.2). Inspired by a number of ingenious experiments that showed an intimate relationship between electricity and magnetism, Maxwell developed a theory that describes both electricity and magnetism with only a small number of elegant equations. It is this theory that gives us important insights into the nature and behavior of light.



Figure 5.2 : James Clerk Maxwell (1831–1879). Maxwell unified the rules governing electricity and magnetism into a coherent theory.

Maxwell's Theory of Electromagnetism

We will look at the structure of the atom in more detail later, but we begin by noting that the typical atom consists of several types of particles, a number of which have not only mass but an additional property called electric charge. In the nucleus (central part) of

every atom are *protons*, which are positively charged; outside the nucleus are electrons, which have a negative charge.

Maxwell's theory deals with these electric charges and their effects, especially when they are moving. In the vicinity of an electron charge, another charge feels a force of attraction or repulsion: opposite charges attract; like charges repel. When charges are not in motion, we observe only this electric attraction or repulsion. If charges are in motion, however (as they are inside every atom and in a wire carrying a current), then we measure another force called *magnetism*.

Magnetism was well known for much of recorded human history, but its cause was not understood until the nineteenth century. Experiments with electric charges demonstrated that magnetism was the result of moving charged particles. Sometimes, the motion is clear, as in the coils of heavy wire that make an industrial electromagnet. Other times, it is more subtle, as in the kind of magnet you buy in a hardware store, in which many of the electrons inside the atoms are spinning in roughly the same direction; it is the alignment of their motion that causes the material to become magnetic.

Physicists use the word *field* to describe the action of forces that one object exerts on other distant objects. For example, we say the Sun produces a *gravitational field* that controls Earth's orbit, even though the Sun and Earth do not come directly into contact. Using this terminology, we can say that stationary electric charges produce *electric fields*, and moving electric charges also produce *magnetic fields*.

Actually, the relationship between electric and magnetic phenomena is even more profound. Experiments showed that changing magnetic fields could produce electric currents (and thus changing electric fields), and changing electric currents could in turn produce changing magnetic fields. So once begun, electric and magnetic field changes could continue to trigger each other.

Maxwell analyzed what would happen if electric charges were oscillating (moving constantly back and forth) and found that the resulting pattern of electric and magnetic fields would spread out and travel rapidly through space. Something similar happens when a raindrop strikes the surface of water or a frog jumps into a pond. The disturbance moves outward and creates a pattern we call a *wave* in the water (Figure 5.3). You might, at first, think that there must be very few situations in nature where electric charges oscillate, but this is not at all the case. As we shall see, atoms and molecules (which consist of charged particles) oscillate back and forth all the time. The resulting electromagnetic disturbances are among the most common phenomena in the universe.



Figure 5.3 : Making Waves. An oscillation in a pool of water creates an expanding disturbance called a wave. (credit: modification of work by "vastateparksstaff"/Flickr)

Maxwell was able to calculate the speed at which an electromagnetic disturbance moves through space; he found that it is equal to the speed of light, which had been measured experimentally. On that basis, he speculated that light was one form of a family of possible electromagnetic disturbances called electromagnetic radiation, a conclusion that was again confirmed in laboratory experiments. When light (reflected from the pages of an astronomy textbook, for example) enters a human eye, its changing electric and magnetic fields stimulate nerve endings, which then transmit the information contained in these changing fields to the brain. The science of astronomy is primarily about analyzing radiation from distant objects to understand what they are and how they work.

The Wave-Like Characteristics of Light

The changing electric and magnetic fields in light are similar to the waves that can be set up in a quiet pool of water. In both cases, the disturbance travels rapidly outward from the point of origin and can use its energy to disturb other things farther away. (For example, in water, the expanding ripples moving away from our frog could disturb the peace of a dragonfly resting on a leaf in the same pool.) In the case of electromagnetic waves, the radiation generated by a transmitting antenna full of charged particles and moving electrons at your local radio station can, sometime later, disturb a group of electrons in your car radio antenna and bring you the news and weather while you are driving to class or work in the morning.

The waves generated by charged particles differ from water waves in some profound ways, however. Water waves require water to travel in. The sound waves we hear, to give another example, are pressure disturbances that require air to travel though. But electromagnetic waves do not require water or air: the fields generate each other and so can move through a vacuum (such as outer space). This was such a disturbing idea to nineteenth-century scientists that they actually made up a substance to fill all of space—one for which there was not a single shred of evidence—just so light waves could have something to travel through: they called it the *aether*. Today, we know that there is no aether and that electromagnetic waves have no trouble at all moving through empty space (as all the starlight visible on a clear night must surely be doing).

The other difference is that *all* electromagnetic waves move at the same speed in empty space (the speed of light—approximately 300,000 kilometers per second, or 300,000,000 meters per second, which can also be written as $3 \times 10^8 \mathrm{m/}$), which turns out to be the fastest possible speed in the universe. No matter where electromagnetic waves are generated from and no matter what other properties they have, when they are moving (and not interacting with matter), they move at the speed of light. Yet you know from everyday experience that there are different kinds of light. For example, we perceive that light waves differ from one another in a property we call color. Let's see how we can denote the differences among the whole broad family of electromagnetic waves.

The nice thing about a wave is that it is a repeating phenomenon. Whether it is the up-and-down motion of a water wave or the changing electric and magnetic fields in a wave of light, the pattern of disturbance repeats in a cyclical way. Thus, any wave motion can be characterized by a series of crests and troughs (Figure 5.4). Moving from one crest through a trough to the next crest completes one cycle. The horizontal length covered by one cycle is called the wavelength. Ocean waves provide an analogy: the wavelength is the distance that separates successive wave crests.

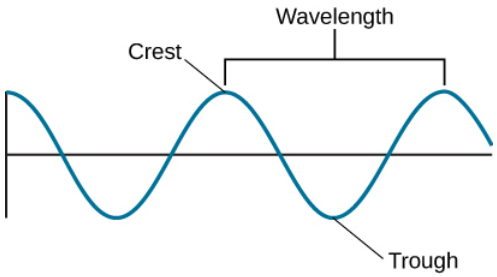


Figure 5.4 : Characterizing Waves. Electromagnetic radiation has wave-like characteristics. The wavelength (λ) is the distance between crests, the frequency (*f*) is the number of cycles per second, and the speed (*c*) is the distance the wave covers during a specified period of time (e.g., kilometers per second).

For visible light, our eyes perceive different wavelengths as different colors: red, for example, is the longest visible wavelength, and violet is the shortest. The main colors of visible light from longest to shortest wavelength can be remembered using the mnemonic ROY G BIV—for Red, Orange, Yellow, Green, Blue, Indigo, and Violet. Other invisible forms of electromagnetic radiation have different wavelengths, as we will see in the next section.

We can also characterize different waves by their frequency, the number of wave cycles that pass by per second. If you count 10 crests moving by each second, for example, then the frequency is 10 cycles per second (cps). In honor of Heinrich Hertz, the physicist who—inspired by Maxwell's work—discovered radio waves, a cps is also called a *hertz* (Hz). Take a look at your radio, for example, and you will see the channel assigned to each radio station is characterized by its frequency, usually in units of KHz (kilohertz, or thousands of hertz) or MHz (megahertz, or millions of hertz).

Wavelength (λ) and frequency (*f*) are related because all electromagnetic waves travel at the same speed. To see how this works, imagine a parade in which everyone is forced by prevailing traffic conditions to move at exactly the same speed. You stand on a corner and watch the waves of marchers come by. First you see row after row of miniature ponies. Because they are not very large and, therefore, have a shorter wavelength, a good number of the ponies can move past you each minute; we can say they have a high frequency. Next, however, come several rows of circus elephants. The elephants are large and marching at the same speed as

the ponies, so far fewer of them can march past you per minute: Because they have a wider spacing (longer wavelength), they represent a lower frequency.

The formula for this relationship can be expressed as follows: for any wave motion, the speed at which a wave moves equals the frequency times the wavelength. Waves with longer wavelengths have lower frequencies. Mathematically, we can express this as

$$c = \lambda f$$

where the Greek letter for "l"—lambda, λ—is used to denote wavelength and c is the scientific symbol for the speed of light. Solving for the wavelength, this is expressed as:

$$\lambda = \frac{c}{f}.$$

Example 5.1: Deriving and Using the Wave Equation

The equation for the relationship between the speed and other characteristics of a wave can be derived from our basic understanding of motion. The average speed of anything that is moving is:

$$\text{average speed} = \frac{\text{distance}}{\text{time}}$$

(So, for example, a car on the highway traveling at a speed of 100 km/h covers 100 km during the time of 1 h.) For an electromagnetic wave to travel the distance of one of its wavelengths, λ, at the speed of light, c, we have $c = \frac{\lambda}{t}$. The frequency of a wave is the number of cycles per second. If a wave has a frequency of a million cycles per second, then the time for each cycle to go by is a millionth of a second. So, in general, $t = \frac{1}{f}$. Substituting into our wave equation, we get $c = \lambda \times f$. Now let's use this to calculate an example. What is the wavelength of visible light that has a frequency of $5.66 \times 10^{14}\text{Hz}$?

Solution

Solving the wave equation for wavelength, we find:

$$\lambda = \frac{c}{f}$$

Substituting our values gives:

$$\lambda = \frac{3.00 \times 10^{8}\ \text{m/s}}{5.66 \times 10^{14}\ \text{Hz}} = 5.30 \times 10^{-7}\ \text{m}$$

This answer can also be written as 530 nm, which is in the yellow-green part of the visible spectrum (nm stands for nanometers, where the term "nano" means "billionths").

Exercise 5.2.1

"Tidal waves," or tsunamis, are waves caused by earthquakes that travel rapidly through the ocean. If a tsunami travels at the speed of 600 km/h and approaches a shore at a rate of one wave crest every 15 min (4 waves/h), what would be the distance between those wave crests at sea?

Answer

$$\lambda = \frac{600\ \text{km/h}}{4\ \text{waves/h}} = 150\ \text{km}$$

Light as a Photon

The electromagnetic wave model of light (as formulated by Maxwell) was one of the great triumphs of nineteenth-century science. In 1887, when Heinrich Hertz actually made invisible electromagnetic waves (what today are called radio waves) on one side of a room and detected them on the other side, it ushered in a new era that led to the modern age of telecommunications. His experiment ultimately led to the technologies of television, cell phones, and today's wireless networks around the globe.

However, by the beginning of the twentieth century, more sophisticated experiments had revealed that light behaves in certain ways that cannot be explained by the wave model. Reluctantly, physicists had to accept that sometimes light behaves more like a "particle"—or at least a self-contained packet of energy—than a wave. We call such a packet of electromagnetic energy a photon.

The fact that light behaves like a wave in certain experiments and like a particle in others was a very surprising and unlikely idea. After all, our common sense says that waves and particles are opposite concepts. On one hand, a wave is a repeating disturbance that, by its very nature, is not in only one place, but spreads out. A particle, on the other hand, is something that can be in only one place at any given time. Strange as it sounds, though, countless experiments now confirm that electromagnetic radiation can sometimes behave like a wave and at other times like a particle.

Then, again, perhaps we shouldn't be surprised that something that always travels at the "speed limit" of the universe and doesn't need a medium to travel through might not obey our everyday common sense ideas. The confusion that this wave-particle duality of light caused in physics was eventually resolved by the introduction of a more complicated theory of waves and particles, now called quantum mechanics. (This is one of the most interesting fields of modern science, but it is mostly beyond the scope of our book. If you are interested in it, see some of the suggested resources at the end of this chapter.)

In any case, you should now be prepared when scientists (or the authors of this book) sometimes discuss electromagnetic radiation as if it consisted of waves and at other times refer to it as a stream of photons. A photon (being a packet of energy) carries a specific amount of energy. We can use the idea of energy to connect the photon and wave models. How much energy a photon has depends on its frequency when you think about it as a wave. A low-energy radio wave has a low frequency as a wave, while a high-energy X-ray at your dentist's office is a high-frequency wave. Among the colors of visible light, violet-light photons have the highest energy and red-light photons have the lowest.

Test whether the connection between photons and waves is clear to you. In the above example, which photon would have the longer wavelength as a wave: the radio wave or the X-ray? If you answered the radio wave, you are correct. Radio waves have a lower frequency, so the wave cycles are longer (they are elephants, not miniature ponies).

Propagation of Light

Let's think for a moment about how light from a lightbulb moves through space. As waves expand, they travel away from the bulb, not just toward your eyes but in all directions. They must therefore cover an ever-widening space. Yet the total amount of light available can't change once the light has left the bulb. This means that, as the same expanding shell of light covers a larger and larger area, there must be less and less of it in any given place. Light (and all other electromagnetic radiation) gets weaker and weaker as it gets farther from its source.

The increase in the area that the light must cover is proportional to the square of the distance that the light has traveled (Figure 5.5). If we stand twice as far from the source, our eyes will intercept two-squared (2×2), or four times less light. If we stand 10 times farther from the source, we get 10-squared, or 100 times less light. You can see how this weakening means trouble for sources of light at astronomical distances. One of the nearest stars, Alpha Centauri A, emits about the same total energy as the Sun. But it is about 270,000 times farther away, and so it appears about 73 billion times fainter. No wonder the stars, which close-up would look more or less like the Sun, look like faint pinpoints of light from far away.

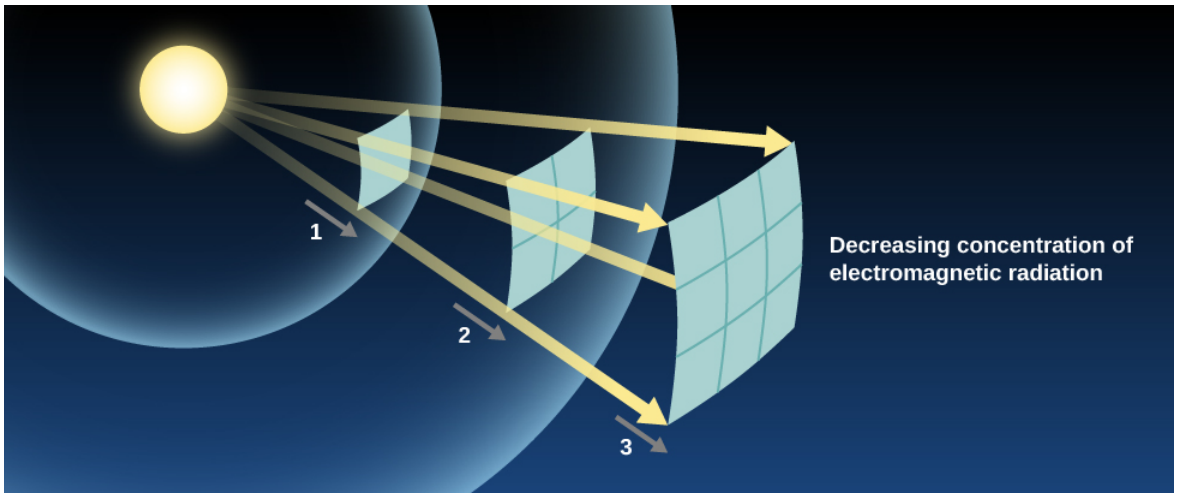


Figure 5.5 : Inverse Square Law for Light. As light radiates away from its source, it spreads out in such a way that the energy per unit area (the amount of energy passing through one of the small squares) decreases as the square of the distance from its source.

This idea—that the apparent brightness of a source (how bright it looks to us) gets weaker with distance in the way we have described—is known as the inverse square law for light propagation. In this respect, the propagation of light is similar to the effects of gravity. Remember that the force of gravity between two attracting masses is also inversely proportional to the square of their separation.

Example 5.2: The Inverse Square Law for Light

The intensity of a 120-W lightbulb observed from a distance 2 m away is 2.4 W/m^2. What would be the intensity if this distance was doubled?

Solution

If we move twice as far away, then the answer will change according to the inverse square of the distance, so the new intensity will be $\left(\frac{1}{2}\right)^2 = \frac{1}{4}$ of the original intensity, or 0.6 W/m^2.

Exercise 5.2.1

How many times brighter or fainter would a star appear if it were moved to:

a. twice its present distance?
b. ten times its present distance?
c. half its present distance?

Answer

a. $\left(\frac{1}{2}\right)^2 = \frac{1}{4}$; b. $\left(\frac{1}{10}\right)^2 = \frac{1}{100}$; c. $\left(\frac{1}{1/2}\right)^2 = 4$

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5.3: The Electromagnetic Spectrum

Learning Objectives

By the end of this section, you will be able to:

- Understand the bands of the electromagnetic spectrum and how they differ from one another
- Understand how each part of the spectrum interacts with Earth's atmosphere
- Explain how and why the light emitted by an object depends on its temperature

Objects in the universe send out an enormous range of electromagnetic radiation. Scientists call this range the electromagnetic spectrum, which they have divided into a number of categories. The spectrum is shown in Figure 5.6, with some information about the waves in each part or band.

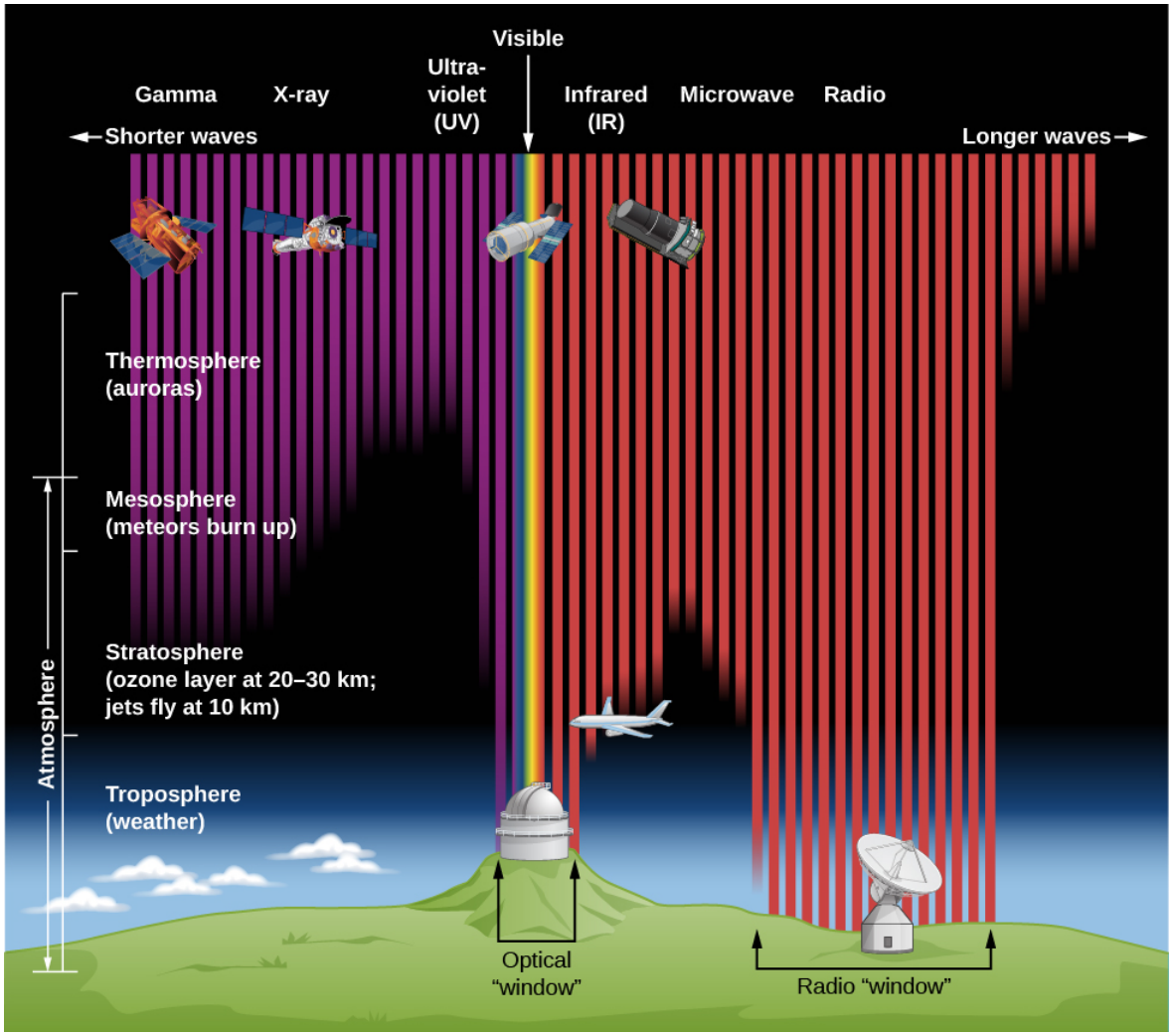


Figure 5.6 : Radiation and Earth's Atmosphere. This figure shows the bands of the electromagnetic spectrum and how well Earth's atmosphere transmits them. Note that high-frequency waves from space do not make it to the surface and must therefore be observed from space. Some infrared and microwaves are absorbed by water and thus are best observed from high altitudes. Low-frequency radio waves are blocked by Earth's ionosphere. (credit: modification of work by STScI/JHU/NASA)

Types of Electromagnetic Radiation

Electromagnetic radiation with the shortest wavelengths, no longer than 0.01 nanometer, is categorized as gamma rays (1 nanometer = 10^{-9} meters; see Appendix D). The name *gamma* comes from the third letter of the Greek alphabet: gamma rays were the third kind of radiation discovered coming from radioactive atoms when physicists first investigated their behavior. Because

gamma rays carry a lot of energy, they can be dangerous for living tissues. Gamma radiation is generated deep in the interior of stars, as well as by some of the most violent phenomena in the universe, such as the deaths of stars and the merging of stellar corpses. Gamma rays coming to Earth are absorbed by our atmosphere before they reach the ground (which is a good thing for our health); thus, they can only be studied using instruments in space.

Electromagnetic radiation with wavelengths between 0.01 nanometer and 20 nanometers is referred to as X-rays. Being more energetic than visible light, X-rays are able to penetrate soft tissues but not bones, and so allow us to make images of the shadows of the bones inside us. While X-rays can penetrate a short length of human flesh, they are stopped by the large numbers of atoms in Earth's atmosphere with which they interact. Thus, X-ray astronomy (like gamma-ray astronomy) could not develop until we invented ways of sending instruments above our atmosphere (Figure 5.7).

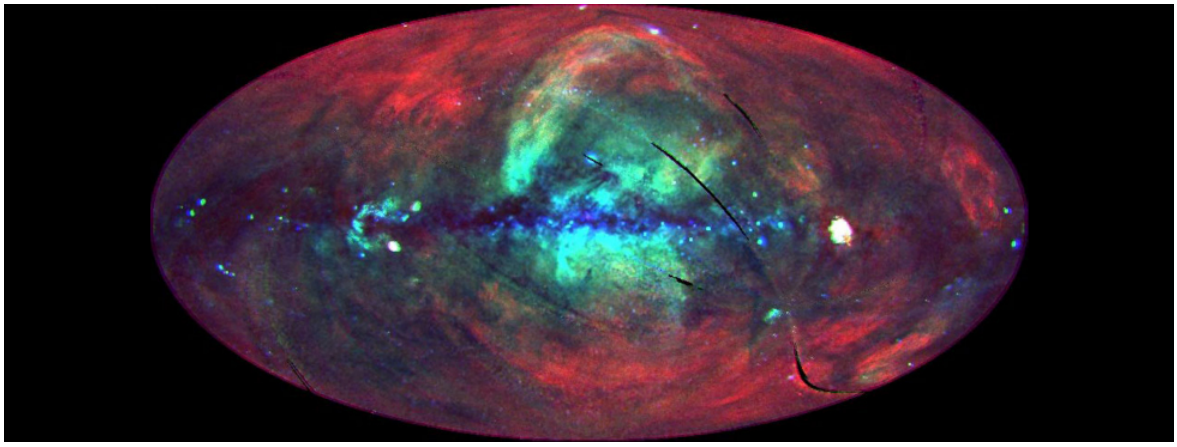


Figure 5.7 : X-Ray Sky. This is a map of the sky tuned to certain types of X-rays (seen from above Earth's atmosphere). The map tilts the sky so that the disk of our Milky Way Galaxy runs across its center. It was constructed and artificially colored from data gathered by the European ROSAT satellite. Each color (red, yellow, and blue) shows X-rays of different frequencies or energies. For example, red outlines the glow from a hot local bubble of gas all around us, blown by one or more exploding stars in our cosmic vicinity. Yellow and blue show more distant sources of X-rays, such as remnants of other exploded stars or the active center of our Galaxy (in the middle of the picture). (credit: modification of work by NASA)

Radiation intermediate between X-rays and visible light is ultraviolet (meaning higher energy than violet). Outside the world of science, ultraviolet light is sometimes called "black light" because our eyes cannot see it. Ultraviolet radiation is mostly blocked by the ozone layer of Earth's atmosphere, but a small fraction of ultraviolet rays from our Sun do penetrate to cause sunburn or, in extreme cases of overexposure, skin cancer in human beings. Ultraviolet astronomy is also best done from space.

Electromagnetic radiation with wavelengths between roughly 400 and 700 nm is called visible light because these are the waves that human vision can perceive. This is also the band of the electromagnetic spectrum that most readily reaches Earth's surface. These two observations are not coincidental: human eyes evolved to see the kinds of waves that arrive from the Sun most effectively. Visible light penetrates Earth's atmosphere effectively, except when it is temporarily blocked by clouds.

Between visible light and radio waves are the wavelengths of infrared or heat radiation. Astronomer William Herschel first discovered infrared in 1800 while trying to measure the temperatures of different colors of sunlight spread out into a spectrum. He noticed that when he accidently positioned his thermometer beyond the reddest color, it still registered heating due to some invisible energy coming from the Sun. This was the first hint about the existence of the other (invisible) bands of the electromagnetic spectrum, although it would take many decades for our full understanding to develop.

A heat lamp radiates mostly infrared radiation, and the nerve endings in our skin are sensitive to this band of the electromagnetic spectrum. Infrared waves are absorbed by water and carbon dioxide molecules, which are more concentrated low in Earth's atmosphere. For this reason, infrared astronomy is best done from high mountaintops, high-flying airplanes, and spacecraft.

After infrared comes the familiar microwave, used in short-wave communication and microwave ovens. (Wavelengths vary from 1 millimeter to 1 meter and are absorbed by water vapor, which makes them effective in heating foods.) The "micro-" prefix refers to the fact that microwaves are small in comparison to radio waves, the next on the spectrum. You may remember that tea—which is full of water—heats up quickly in your microwave oven, while a ceramic cup—from which water has been removed by baking—stays cool in comparison.

All electromagnetic waves longer than microwaves are called radio waves, but this is so broad a category that we generally divide it into several subsections. Among the most familiar of these are radar waves, which are used in radar guns by traffic officers to determine vehicle speeds, and AM radio waves, which were the first to be developed for broadcasting. The wavelengths of these different categories range from over a meter to hundreds of meters, and other radio radiation can have wavelengths as long as several kilometers.

With such a wide range of wavelengths, not all radio waves interact with Earth's atmosphere in the same way. FM and TV waves are not absorbed and can travel easily through our atmosphere. AM radio waves are absorbed or reflected by a layer in Earth's atmosphere called the ionosphere (the ionosphere is a layer of charged particles at the top of our atmosphere, produced by interactions with sunlight and charged particles that are ejected from the Sun).

We hope this brief survey has left you with one strong impression: although visible light is what most people associate with astronomy, the light that our eyes can see is only a tiny fraction of the broad range of waves generated in the universe. Today, we understand that judging some astronomical phenomenon by using only the light we can see is like hiding under the table at a big dinner party and judging all the guests by nothing but their shoes. There's a lot more to each person than meets our eye under the table. It is very important for those who study astronomy today to avoid being "visible light chauvinists"—to respect only the information seen by their eyes while ignoring the information gathered by instruments sensitive to other bands of the electromagnetic spectrum.

Table 5.1 summarizes the bands of the electromagnetic spectrum and indicates the temperatures and typical astronomical objects that emit each kind of electromagnetic radiation. While at first, some of the types of radiation listed in the table may seem unfamiliar, you will get to know them better as your astronomy course continues. You can return to this table as you learn more about the types of objects astronomers study.

Table 5.1: Types of Electromagnetic Radiation

Type of Radiation	Wavelength Range (nm)	Radiated by Objects at This Temperature	Typical Sources
Gamma rays	Less than 0.01	More than 10^8 K	Produced in nuclear reactions; require very high-energy processes
X-rays	0.01–20	10^6–10^8 K	Gas in clusters of galaxies, supernova remnants, solar corona
Ultraviolet	20–400	10^4–10^6 K	Supernova remnants, very hot stars
Visible	400–700	10^3–10^4 K	Stars
Infrared	10^3–10^6	10–10^3 K	Cool clouds of dust and gas, planets, moons
Microwave	10^6–10^9	Less than 10 K	Active galaxies, pulsars, cosmic background radiation
Radio	More than 10^9	Less than 10 K	Supernova remnants, pulsars, cold gas

Radiation and Temperature

Some astronomical objects emit mostly infrared radiation, others mostly visible light, and still others mostly ultraviolet radiation. What determines the type of electromagnetic radiation emitted by the Sun, stars, and other dense astronomical objects? The answer often turns out to be their *temperature*.

At the microscopic level, everything in nature is in motion. A solid is composed of molecules and atoms in continuous vibration: they move back and forth in place, but their motion is much too small for our eyes to make out. A gas consists of atoms and/or molecules that are flying about freely at high speed, continually bumping into one another and bombarding the surrounding matter.

The hotter the solid or gas, the more rapid the motion of its molecules or atoms. The temperature of something is thus a measure of the average motion energy of the particles that make it up.

This motion at the microscopic level is responsible for much of the electromagnetic radiation on Earth and in the universe. As atoms and molecules move about and collide, or vibrate in place, their electrons give off electromagnetic radiation. The characteristics of this radiation are determined by the temperature of those atoms and molecules. In a hot material, for example, the individual particles vibrate in place or move rapidly from collisions, so the emitted waves are, on average, more energetic. And recall that higher energy waves have a higher frequency. In very cool material, the particles have low-energy atomic and molecular motions and thus generate lower-energy waves.

Link to Learning

Check out the NASA briefing or NASA's 5-minute introductory video to learn more about the electromagnetic spectrum.

Radiation Laws

To understand, in more quantitative detail, the relationship between temperature and electromagnetic radiation, we imagine an idealized object called a blackbody. Such an object (unlike your sweater or your astronomy instructor's head) does not reflect or scatter any radiation, but absorbs all the electromagnetic energy that falls onto it. The energy that is absorbed causes the atoms and molecules in it to vibrate or move around at increasing speeds. As it gets hotter, this object will radiate electromagnetic waves until absorption and radiation are in balance. We want to discuss such an idealized object because, as you will see, stars behave in very nearly the same way.

The radiation from a blackbody has several characteristics, as illustrated in Figure 5.8. The graph shows the power emitted at each wavelength by objects of different temperatures. In science, the word *power* means the energy coming off per second (and it is typically measured in *watts*, which you are probably familiar with from buying lightbulbs).

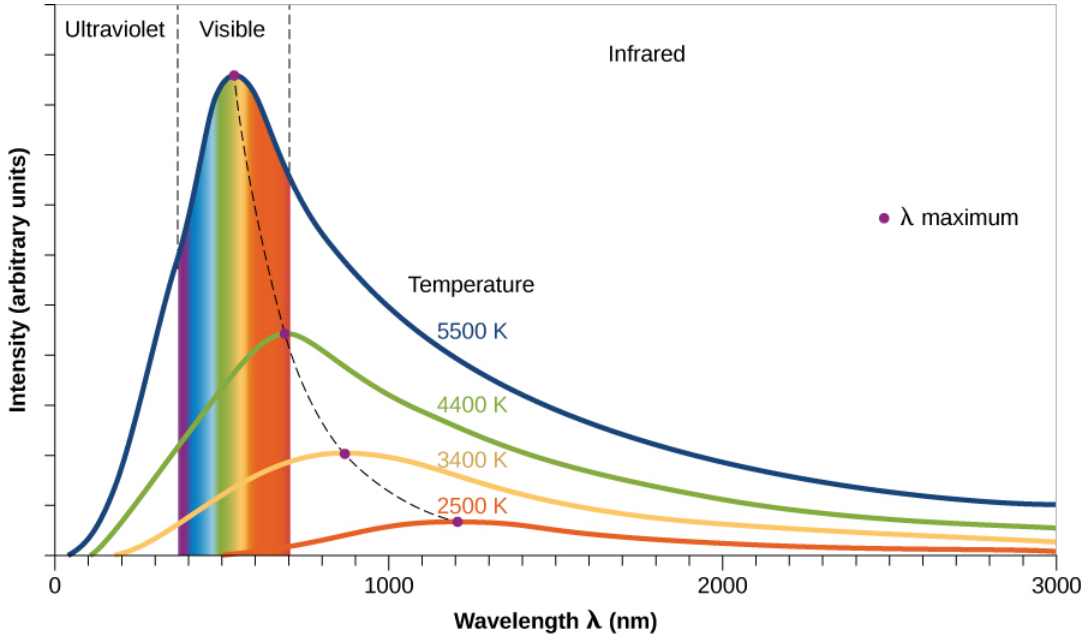


Figure 5.8 : Radiation Laws Illustrated. This graph shows in arbitrary units how many photons are given off at each wavelength for objects at four different temperatures. The wavelengths corresponding to visible light are shown by the colored bands. Note that at hotter temperatures, more energy (in the form of photons) is emitted at all wavelengths. The higher the temperature, the shorter the wavelength at which the peak amount of energy is radiated (this is known as Wien's law).

First of all, notice that the curves show that, at each temperature, our blackbody object emits radiation (photons) at all wavelengths (all colors). This is because in any solid or denser gas, some molecules or atoms vibrate or move between collisions slower than average and some move faster than average. So when we look at the electromagnetic waves emitted, we find a broad range, or spectrum, of energies and wavelengths. More energy is emitted at the average vibration or motion rate (the highest part of each curve), but if we have a large number of atoms or molecules, some energy will be detected at each wavelength.

Second, note that an object at a higher temperature emits more power at all wavelengths than does a cooler one. In a hot gas (the taller curves in Figure 5.8), for example, the atoms have more collisions and give off more energy. In the real world of stars, this means that hotter stars give off more energy at every wavelength than do cooler stars.

Third, the graph shows us that the higher the temperature, the shorter the wavelength at which the maximum power is emitted. Remember that a shorter wavelength means a higher frequency and energy. It makes sense, then, that hot objects give off a larger fraction of their energy at shorter wavelengths (higher energies) than do cool objects. You may have observed examples of this rule in everyday life. When a burner on an electric stove is turned on low, it emits only heat, which is infrared radiation, but does not glow with visible light. If the burner is set to a higher temperature, it starts to glow a dull red. At a still-higher setting, it glows a brighter orange-red (shorter wavelength). At even higher temperatures, which cannot be reached with ordinary stoves, metal can appear brilliant yellow or even blue-white.

We can use these ideas to come up with a rough sort of "thermometer" for measuring the temperatures of stars. Because many stars give off most of their energy in visible light, the color of light that dominates a star's appearance is a rough indicator of its temperature. If one star looks red and another looks blue, which one has the higher temperature? Because blue is the shorter-wavelength color, it is the sign of a hotter star. (Note that the temperatures we associate with different colors in science are not the same as the ones artists use. In art, red is often called a "hot" color and blue a "cool" color. Likewise, we commonly see red on faucet or air conditioning controls to indicate hot temperatures and blue to indicate cold temperatures. Although these are common uses to us in daily life, in nature, it's the other way around.)

We can develop a more precise star thermometer by measuring how much energy a star gives off at each wavelength and by constructing diagrams like Figure 5.8. The location of the peak (or maximum) in the power curve of each star can tell us its temperature. The average temperature at the surface of the Sun, which is where the radiation that we see is emitted, turns out to be 5800 K. (Throughout this text, we use the kelvin or absolute temperature scale. On this scale, water freezes at 273 K and boils at 373 K. All molecular motion ceases at 0 K. The various temperature scales are described in Appendix D.) There are stars cooler than the Sun and stars hotter than the Sun.

The wavelength at which maximum power is emitted can be calculated according to the equation

$$\lambda_{\text{max}} = \frac{3 \times 10^6}{T}$$

where the wavelength is in nanometers (one billionth of a meter) and the temperature is in K (the constant

Unexpected text node: 'Table 5.1.'

Example 5.3: Calculating the Temperature of a Blackbody

We can use Wien's law to calculate the temperature of a star provided we know the wavelength of peak intensity for its spectrum. If the emitted radiation from a red dwarf star has a wavelength of maximum power at 1200 nm, what is the temperature of this star, assuming it is a blackbody?

Solution

Solving Wien's law for temperature gives:

$$T = \frac{3 \times 10^6 \text{ nm K}}{\lambda_{\text{max}}} = \frac{3 \times 10^6 \text{ nm K}}{1200 \text{ nm}} = 2500 \text{ K}$$

Exercise 5.3.1

What is the temperature of a star whose maximum light is emitted at a much shorter wavelength of 290 nm?

Answer

$$T = \frac{3 \times 10^6 \text{ nm K}}{\lambda_{\text{max}}} = \frac{3 \times 10^6 \text{ nm K}}{290 \text{ nm}} = 10{,}300 \text{ K}$$

Since this star has a peak wavelength that is at a shorter wavelength (in the ultraviolet part of the spectrum) than that of our Sun (in the visible part of the spectrum), it should come as no surprise that its surface temperature is much hotter than our Sun's.

We can also describe our observation that hotter objects radiate more power at all wavelengths in a mathematical form. If we sum up the contributions from all parts of the electromagnetic spectrum, we obtain the total energy emitted by a blackbody. What we usually measure from a large object like a star is the energy flux, the power emitted per square meter. The word *flux* means "flow" here: we are interested in the flow of power into an area (like the area of a telescope mirror). It turns out that the energy flux from a blackbody at temperature *T* is proportional to the fourth power of its absolute temperature. This relationship is known as the Stefan-Boltzmann law and can be written in the form of an equation as

$$F = \sigma T^4$$

where *F* stands for the energy flux (in units of watts per square meter), T is given in Kelvins, and σ (Greek letter sigma) is a constant number $\left(5.67 \times 10^{-8}\right)$.

Notice how impressive this result is. Increasing the temperature of a star would have a tremendous effect on the power it radiates. If the Sun, for example, were twice as hot—that is, if it had a temperature of 11,600 K—it would radiate 2^4, or 16 times more power than it does now. Tripling the temperature would raise the power output 81 times. Hot stars really shine away a tremendous amount of energy.

Example 5.4: Calculating the Power of a Star

While energy flux tells us how much power a star emits per square meter, we would often like to know how much total power is emitted by the star. We can determine that by multiplying the energy flux by the number of square meters on the surface of the star. Stars are mostly spherical, so we can use the formula $4\pi R^2$ for the surface area, where *R* is the radius of the star. The total power emitted by the star (which we call the star's "absolute luminosity") can be found by multiplying the formula for energy flux and the formula for the surface area:

$$L = 4\pi R^2 \sigma T^4$$

Two stars have the same size and are the same distance from us. Star A has a surface temperature of 6000 K, and star B has a surface temperature twice as high, 12,000 K. How much more luminous is star B compared to star A?

Solution

$$L_\mathrm{A} = 4\pi {R_\mathrm{A}}^2 \sigma {T_\mathrm{A}}^4 \text{ and } L_\mathrm{B} = 4\pi {R_\mathrm{B}}^2 \sigma {T_\mathrm{B}}^4$$

Take the ratio of the luminosity of Star A to Star B:

$$\frac{L_\mathrm{B}}{L_\mathrm{A}} = \frac{4\pi {R_\mathrm{B}}^2 \sigma {T_\mathrm{B}}^4}{4\pi {R_\mathrm{A}}^2 \sigma {T_\mathrm{A}}^4} = \frac{{R_\mathrm{B}}^2 {T_\mathrm{B}}^4}{{R_\mathrm{A}}^2 {T_\mathrm{A}}^4}$$

Because the two stars are the same size, $R_\mathrm{A} = R_\mathrm{B}$, leaving

$$\frac{{T_\mathrm{B}}^4}{{T_\mathrm{A}}^4} = \frac{(12{,}000\ \mathrm{K})^4}{(6000\ \mathrm{K})^4} = 2^4 = 16$$

Exercise 5.3.1

Two stars with identical diameters are the same distance away. One has a temperature of 8700 K and the other has a temperature of 2900 K. Which is brighter? How much brighter is it?

Answer

The 8700 K star has triple the temperature, so it is 3^4 = 81 times brighter.

Link to Learning

You can use the Blackbody Spectrum simulator to explore the relationship between an object's temperature, peak wavelength, overall brightness, and apparent color.

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5.4: Spectroscopy in Astronomy

Learning Objectives

By the end of this section, you will be able to:

- Describe the properties of light
- Explain how astronomers learn the composition of a gas by examining its spectral lines
- Discuss the various types of spectra

Electromagnetic radiation carries a lot of information about the nature of stars and other astronomical objects. To extract this information, however, astronomers must be able to study the amounts of energy we receive at different wavelengths of light in fine detail. Let's examine how we can do this and what we can learn.

Properties of Light

Light exhibits certain behaviors that are important to the design of telescopes and other instruments. For example, light can be *reflected* from a surface. If the surface is smooth and shiny, as with a mirror, the direction of the reflected light beam can be calculated accurately from knowledge of the shape of the reflecting surface. Light is also bent, or *refracted*, when it passes from one kind of transparent material into another—say, from the air into a glass lens.

Reflection and refraction of light are the basic properties that make possible all *optical* instruments (devices that help us to see things better)—from eyeglasses to giant astronomical telescopes. Such instruments are generally combinations of glass lenses, which bend light according to the principles of refraction, and curved mirrors, which depend on the properties of reflection. Small optical devices, such as eyeglasses or binoculars, generally use lenses, whereas large telescopes depend almost entirely on mirrors for their main optical elements. We will discuss astronomical instruments and their uses more fully in Astronomical Instruments. For now, we turn to another behavior of light, one that is essential for the decoding of light.

In 1672, in the first paper that he submitted to the Royal Society, Sir Isaac Newton described an experiment in which he permitted sunlight to pass through a small hole and then through a prism. Newton found that sunlight, which looks white to us, is actually made up of a mixture of all the colors of the rainbow (Figure 5.9).

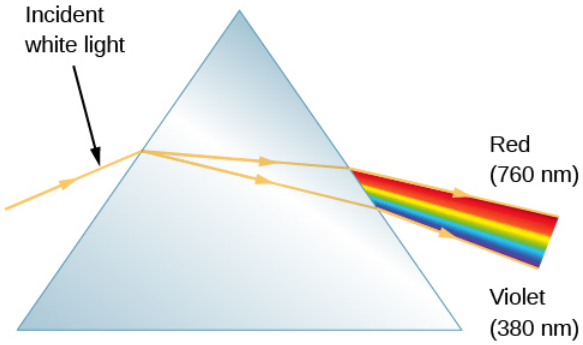


Figure 5.9 : Action of a Prism. When we pass a beam of white sunlight through a prism, we see a rainbow-colored band of light that we call a continuous spectrum.

Figure 5.9 shows how light is separated into different colors with a prism—a piece of glass in the shape of a triangle with refracting surfaces. Upon entering one face of the prism, the path of the light is refracted (bent), but not all of the colors are bent by the same amount. The bending of the beam depends on the wavelength of the light as well as the properties of the material, and as a result, different wavelengths (or colors of light) are bent by different amounts and therefore follow slightly different paths through the prism. The violet light is bent more than the red. This phenomenon is called dispersion and explains Newton's rainbow experiment.

Upon leaving the opposite face of the prism, the light is bent again and further dispersed. If the light leaving the prism is focused on a screen, the different wavelengths or colors that make up white light are lined up side by side just like a rainbow (Figure 5.10). (In fact, a rainbow is formed by the dispersion of light though raindrops; see The Rainbow feature box.) Because this array of colors is a spectrum of light, the instrument used to disperse the light and form the spectrum is called a spectrometer.

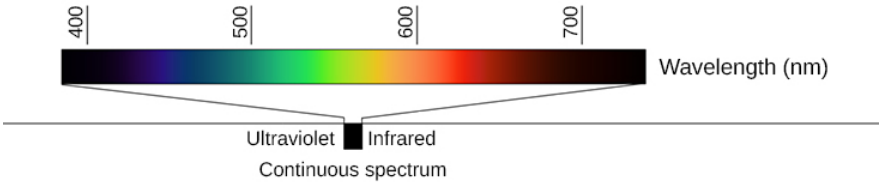


Figure 5.10 : Continuous Spectrum. When white light passes through a prism, it is dispersed and forms a continuous spectrum of all the colors. Although it is hard to see in this printed version, in a well-dispersed spectrum, many subtle gradations in color are visible as your eye scans from one end (violet) to the other (red).

The Value of Stellar Spectra

When Newton described the laws of refraction and dispersion in optics, and observed the solar spectrum, all he could see was a continuous band of colors. If the spectrum of the white light from the Sun and stars were simply a continuous rainbow of colors, astronomers would have little interest in the detailed study of a star's spectrum once they had learned its average surface temperature. In 1802, however, William Wollaston built an improved spectrometer that included a lens to focus the Sun's spectrum on a screen. With this device, Wollaston saw that the colors were not spread out uniformly, but instead, some ranges of color were missing, appearing as dark bands in the solar spectrum. He mistakenly attributed these lines to natural boundaries between the colors. In 1815, German physicist Joseph Fraunhofer, upon a more careful examination of the solar spectrum, found about 600 such dark lines (missing colors), which led scientists to rule out the boundary hypothesis (Figure 5.11).

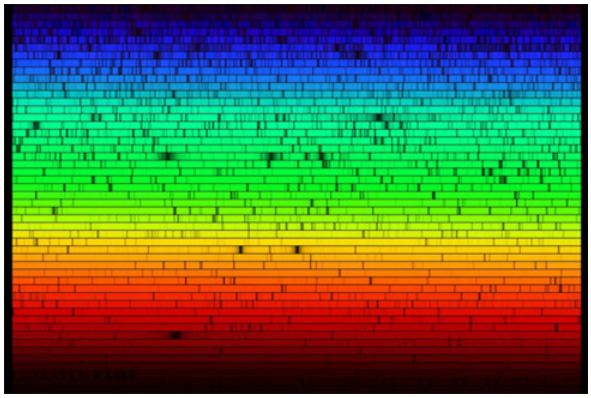


Figure 5.11 : Visible Spectrum of the Sun. Our star's spectrum is crossed by dark lines produced by atoms in the solar atmosphere that absorb light at certain wavelengths. (credit: modification of work by Nigel Sharp, NOAO/National Solar Observatory at Kitt Peak/AURA, and the National Science Foundation)

Later, researchers found that similar dark lines could be produced in the spectra ("spectra" is the plural of "spectrum") of artificial light sources. They did this by passing their light through various apparently transparent substances—usually containers with just a bit of thin gas in them.

These gases turned out not to be transparent at *all* colors: they were quite opaque at a few sharply defined wavelengths. Something in each gas had to be absorbing just a few colors of light and no others. All gases did this, but each different element absorbed a different set of colors and thus showed different dark lines. If the gas in a container consisted of two elements, then light passing through it was missing the colors (showing dark lines) for both of the elements. So it became clear that certain lines in the spectrum "go with" certain elements. This discovery was one of the most important steps forward in the history of astronomy.

What would happen if there were no continuous spectrum for our gases to remove light from? What if, instead, we heated the same thin gases until they were hot enough to glow with their own light? When the gases were heated, a spectrometer revealed no continuous spectrum, but several separate bright lines. That is, these hot gases emitted light only at certain specific wavelengths or colors.

When the gas was pure hydrogen, it would emit one pattern of colors; when it was pure sodium, it would emit a different pattern. A mixture of hydrogen and sodium emitted both sets of spectral lines. The colors the gases emitted when they were heated were the very same colors as those they had absorbed when a continuous source of light was behind them. From such experiments, scientists

began to see that different substances showed distinctive *spectral signatures* by which their presence could be detected (Figure 5.12). Just as your signature allows the bank to identify you, the unique pattern of colors for each type of atom (its spectrum) can help us identify which element or elements are in a gas.

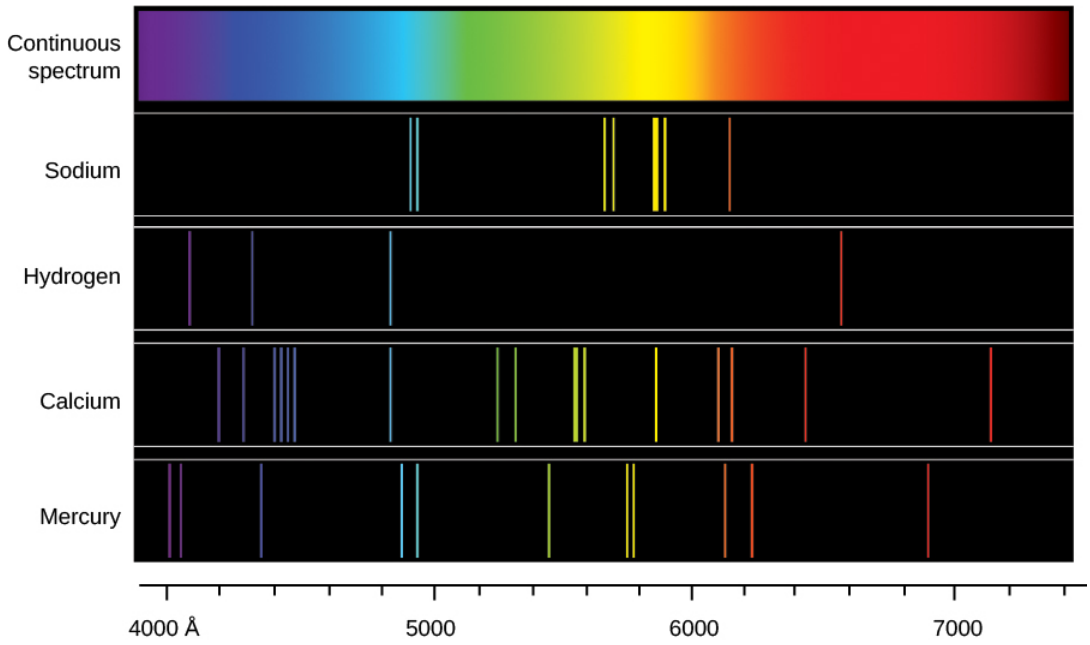


Figure 5.12 : Continuous Spectrum and Line Spectra from Different Elements. Each type of glowing gas (each element) produces its own unique pattern of lines, so the composition of a gas can be identified by its spectrum. The spectra of sodium, hydrogen, calcium, and mercury gases are shown here.

Types of Spectra

In these experiments, then, there were three different types of spectra. A continuous spectrum (formed when a solid or very dense gas gives off radiation) is an array of all wavelengths or colors of the rainbow. A continuous spectrum can serve as a backdrop from which the atoms of much less dense gas can absorb light. A dark line, or absorption spectrum, consists of a series or pattern of dark lines—missing colors—superimposed upon the continuous spectrum of a source. A bright line, or emission spectrum, appears as a pattern or series of bright lines; it consists of light in which only certain discrete wavelengths are present. (Figure 5.11 shows an absorption spectrum, whereas Figure 5.12 shows the emission spectrum of a number of common elements along with an example of a continuous spectrum.)

When we have a hot, thin gas, each particular chemical element or compound produces its own characteristic pattern of spectral lines—its spectral signature. No two types of atoms or molecules give the same patterns. In other words, each particular gas can absorb or emit only certain wavelengths of the light peculiar to that gas. In contrast, absorption spectra occur when passing white light through a cool, thin gas. The temperature and other conditions determine whether the lines are bright or dark (whether light is absorbed or emitted), but the wavelengths of the lines for any element are the same in either case. It is the precise pattern of wavelengths that makes the signature of each element unique. Liquids and solids can also generate spectral lines or bands, but they are broader and less well defined—and hence, more difficult to interpret. Spectral analysis, however, can be quite useful. It can, for example, be applied to light reflected off the surface of a nearby asteroid as well as to light from a distant galaxy.

The dark lines in the solar spectrum thus give evidence of certain chemical elements between us and the Sun absorbing those wavelengths of sunlight. Because the space between us and the Sun is pretty empty, astronomers realized that the atoms doing the absorbing must be in a thin atmosphere of cooler gas around the Sun. This outer atmosphere is not all that different from the rest of the Sun, just thinner and cooler. Thus, we can use what we learn about its composition as an indicator of what the whole Sun is made of. Similarly, we can use the presence of absorption and emission lines to analyze the composition of other stars and clouds of gas in space.

Such analysis of spectra is the key to modern astronomy. Only in this way can we “sample” the stars, which are too far away for us to visit. Encoded in the electromagnetic radiation from celestial objects is clear information about the chemical makeup of these

objects. Only by understanding what the stars were made of could astronomers begin to form theories about what made them shine and how they evolved.

In 1860, German physicist Gustav Kirchhoff became the first person to use spectroscopy to identify an element in the Sun when he found the spectral signature of sodium gas. In the years that followed, astronomers found many other chemical elements in the Sun and stars. In fact, the element helium was found first in the Sun from its spectrum and only later identified on Earth. (The word "helium" comes from *helios*, the Greek name for the Sun.)

Why are there specific lines for each element? The answer to that question was not found until the twentieth century; it required the development of a model for the atom. We therefore turn next to a closer examination of the atoms that make up all matter.

Link to Learning

You can use the Spectrum Constructor to explore the three types of spectra and how they appear through a diffraction grating when the brightness of each wavelength is measured with a spectrometer.

Making Connections: The Rainbow

Rainbows are an excellent illustration of the dispersion of sunlight. You have a good chance of seeing a rainbow any time you are between the Sun and a rain shower, as illustrated in Figure 5.13. The raindrops act like little prisms and break white light into the spectrum of colors. Suppose a ray of sunlight encounters a raindrop and passes into it. The light changes direction—is refracted—when it passes from air to water; the blue and violet light are refracted more than the red. Some of the light is then reflected at the backside of the drop and reemerges from the front, where it is again refracted. As a result, the white light is spread out into a rainbow of colors.



Figure 5.13 : Rainbow Refraction. (a) This diagram shows how light from the Sun, which is located behind the observer, can be refracted by raindrops to produce (b) a rainbow. (c) Refraction separates white light into its component colors.

Note that violet light lies above the red light after it emerges from the raindrop. When you look at a rainbow, however, the red light is higher in the sky. Why? Look again at Figure 5.13. If the observer looks at a raindrop that is high in the sky, the violet light passes over her head and the red light enters her eye. Similarly, if the observer looks at a raindrop that is low in the sky, the violet light reaches her eye and the drop appears violet, whereas the red light from that same drop strikes the ground and is not seen. Colors of intermediate wavelengths are refracted to the eye by drops that are intermediate in altitude between the drops that appear violet and the ones that appear red. Thus, a single rainbow always has red on the outside and violet on the inside.

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5.5: The Structure of the Atom

Learning Objectives

By the end of this section, you will be able to:

- Describe the structure of atoms and the components of nuclei
- The idea that matter is composed of tiny particles called atoms is at least 25 centuries old. It took until the twentieth century, however, for scientists to invent instruments that permitted them to probe inside an atom and find that it is not, as had been thought, hard and indivisible. Instead, the atom is a complex structure composed of still smaller particles.

Probing the Atom

The first of these smaller particles was discovered by British physicist James (J. J.) Thomson in 1897. Named the *electron*, this particle is negatively charged. (It is the flow of these particles that produces currents of electricity, whether in lightning bolts or in the wires leading to your lamp.) Because an atom in its normal state is electrically neutral, each electron in an atom must be balanced by the same amount of positive charge.

The next step was to determine where in the atom the positive and negative charges are located. In 1911, British physicist Ernest Rutherford devised an experiment that provided part of the answer to this question. He bombarded an extremely thin piece of gold foil, only about 400 atoms thick, with a beam of alpha particles (Figure 5.14). *Alpha particles* (α particles) are helium atoms that have lost their electrons and thus are positively charged. Most of these particles passed though the gold foil just as if it and the atoms in it were nearly empty space. About 1 in 8000 of the alpha particles, however, completely reversed direction and bounced backward from the foil. Rutherford wrote, “It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.”

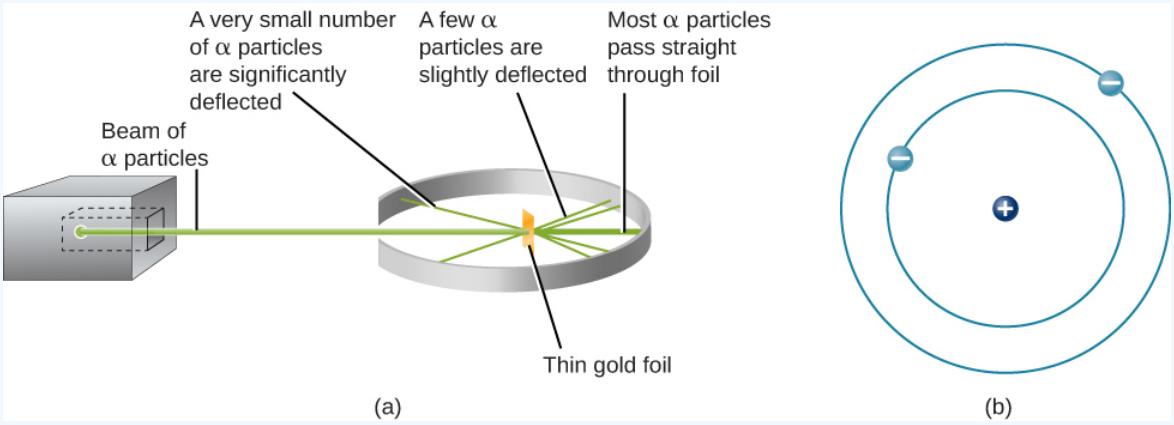


Figure 5.14 : Rutherford’s Experiment. (a) When Rutherford allowed α particles from a radioactive source to strike a target of gold foil, he found that, although most of them went straight through, some rebounded back in the direction from which they came. (b) From this experiment, he concluded that the atom must be constructed like a miniature solar system, with the positive charge concentrated in the nucleus and the negative charge orbiting in the large volume around the nucleus. Note that this drawing is not to scale; the electron orbits are much larger relative to the size of the nucleus.

The only way to account for the particles that reversed direction when they hit the gold foil was to assume that nearly all of the mass, as well as all of the positive charge in each individual gold atom, is concentrated in a tiny center or nucleus. When a positively charged alpha particle strikes a nucleus, it reverses direction, much as a cue ball reverses direction when it strikes another billiard ball. Rutherford’s model placed the other type of charge—the negative electrons—in orbit around this nucleus.

Rutherford’s model required that the electrons be in motion. Positive and negative charges attract each other, so stationary electrons would fall into the positive nucleus. Also, because both the electrons and the nucleus are extremely small, most of the atom is empty, which is why nearly all of Rutherford’s particles were able to pass right through the gold foil without colliding with anything. Rutherford’s model was a very successful explanation of the experiments he conducted, although eventually scientists would discover that even the nucleus itself has structure.

The Atomic Nucleus

The simplest possible atom (and the most common one in the Sun and stars) is hydrogen. The nucleus of ordinary hydrogen contains a single proton. Moving around this proton is a single electron. The mass of an electron is nearly 2000 times smaller than the mass of a proton; the electron carries an amount of charge exactly equal to that of the proton but opposite in sign (Figure 5.15). Opposite charges attract each other, so it is an electromagnetic force that holds the proton and electron together, just as gravity is the force that keeps planets in orbit around the Sun.

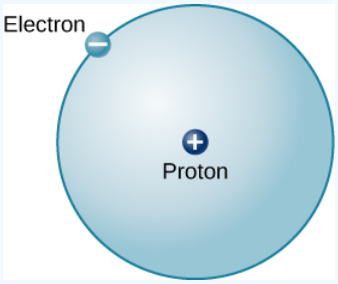


Figure 5.15 : Hydrogen Atom. This is a schematic diagram of a hydrogen atom in its lowest energy state, also called the ground state. The proton and electron have equal but opposite charges, which exert an electromagnetic force that binds the hydrogen atom together. In the illustration, the size of the particles is exaggerated so that you can see them; they are not to scale. They are also shown much closer than they would actually be as it would take more than an entire page to show their actual distance to scale.

There are many other types of atoms in nature. Helium, for example, is the second-most abundant element in the Sun. Helium has two protons in its nucleus instead of the single proton that characterizes hydrogen. In addition, the helium nucleus contains two neutrons, particles with a mass comparable to that of the proton but with no electric charge. Moving around this nucleus are two electrons, so the total net charge of the helium atom is also zero (Figure 5.16).

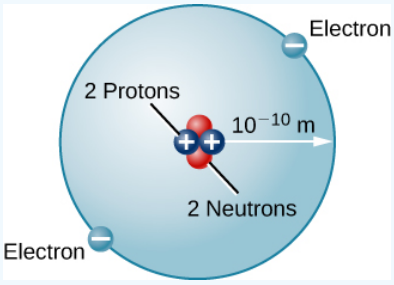


Figure 5.16 : Helium Atom. Here we see a schematic diagram of a helium atom in its lowest energy state. Two protons are present in the nucleus of all helium atoms. In the most common variety of helium, the nucleus also contains two neutrons, which have nearly the same mass as the proton but carry no charge. Two electrons orbit the nucleus.

From this description of hydrogen and helium, perhaps you have guessed the pattern for building up all the elements (different types of atoms) that we find in the universe. The type of element is determined by the number of protons in the nucleus of the atom. For example, any atom with six protons is the element carbon, with eight protons is oxygen, with 26 is iron, and with 92 is uranium. On Earth, a typical atom has the same number of electrons as protons, and these electrons follow complex orbital patterns around the nucleus. Deep inside stars, however, it is so hot that the electrons get loose from the nucleus and (as we shall see) lead separate yet productive lives.

The ratio of neutrons to protons increases as the number of protons increases, but each element is unique. The number of neutrons is not necessarily the same for all atoms of a given element. For example, most hydrogen atoms contain no neutrons at all. There are, however, hydrogen atoms that contain one proton and one neutron, and others that contain one proton and two neutrons. The various types of hydrogen nuclei with different numbers of neutrons are called isotopes of hydrogen (Figure 5.17), and all other elements have isotopes as well. You can think of isotopes as siblings in the same element “family”—closely related but with different characteristics and behaviors.

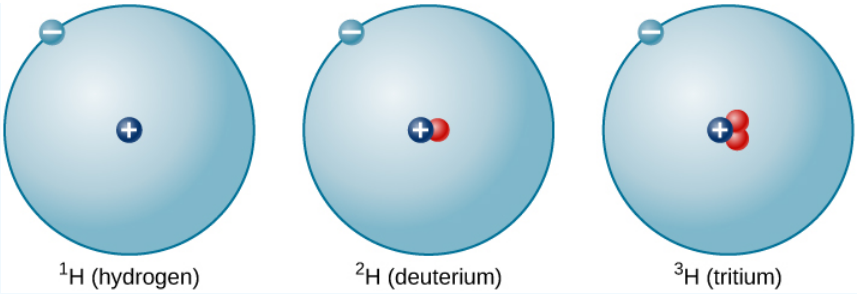


Figure 5.17 : Isotopes of Hydrogen. A single proton in the nucleus defines the atom to be hydrogen, but there may be zero, one, or two neutrons. The most common isotope of hydrogen is the one with only a single proton and no neutrons.

Link to Learning

To explore the structure of atoms, go to the PhET Build an Atom website where you can add protons, neutrons, or electrons to a model and the name of the element you have created will appear. You can also see the net charge, the mass number, whether it is stable or unstable, and whether it is an ion or a neutral atom.

The Bohr Atom

Rutherford's model for atoms has one serious problem. Maxwell's theory of electromagnetic radiation says that when electrons change either speed or the direction of motion, they must emit energy. Orbiting electrons constantly change their direction of motion, so they should emit a constant stream of energy. Applying Maxwell's theory to Rutherford's model, all electrons should spiral into the nucleus of the atom as they lose energy, and this collapse should happen very quickly—in about 10^{-16} seconds.

It was Danish physicist Niels Bohr (1885–1962) who solved the mystery of how electrons remain in orbit. He was trying to develop a model of the atom that would also explain certain regularities observed in the spectrum of hydrogen. He suggested that the spectrum of hydrogen can be understood if we assume that orbits of only certain sizes are possible for the electron. Bohr further assumed that as long as the electron moves in only one of these allowed orbits, it radiates no energy: its energy would change only if it moved from one orbit to another.

This suggestion, in the words of science historian Abraham Pais, was "one of the most audacious hypotheses ever introduced in physics." If something equivalent were at work in the everyday world, you might find that, as you went for a walk after astronomy class, nature permitted you to walk two steps per minute, five steps per minute, and 12 steps per minute, but no speeds in between. No matter how you tried to move your legs, only certain walking speeds would be permitted. To make things more bizarre, it would take no effort to walk at any one of the allowed speeds, but it would be difficult to change from one speed to another. Luckily, no such rules apply at the level of human behavior. But at the microscopic level of the atom, experiment after experiment has confirmed the validity of Bohr's strange idea. Bohr's suggestions became one of the foundations of the new (and much more sophisticated) model of the subatomic world called quantum mechanics.

In Bohr's model, if the electron moves from one orbit to another closer to the atomic nucleus, it must give up some energy in the form of electromagnetic radiation. If the electron goes from an inner orbit to one farther from the nucleus, however, it requires some additional energy. One way to obtain the necessary energy is to absorb electromagnetic radiation that may be streaming past the atom from an outside source.

A key feature of Bohr's model is that each of the permitted electron orbits around a given atom has a certain energy value; we therefore can think of each orbit as an energy level. To move from one orbit to another (which will have its own specific energy value) requires a change in the electron's energy—a change determined by the difference between the two energy values. If the electron goes to a lower level, the energy difference will be given off; if the electron goes to a higher level, the energy difference must be obtained from somewhere else. Each jump (or transition) to a different level has a fixed and definite energy change associated with it.

A crude analogy for this situation might be life in a tower of luxury apartments where the rent is determined by the quality of the view. Such a building has certain, definite numbered levels or floors on which apartments are located. No one can live on floor 5.37 or 22.5. In addition, the rent gets higher as you go up to higher floors. If you want to exchange an apartment on the twentieth floor for one on the second floor, you will not owe as much rent. However, if you want to move from the third floor to the twenty-fifth floor, your rent will increase. In an atom, too, the "cheapest" place for an electron to live is the lowest possible level, and energy is required to move to a higher level.

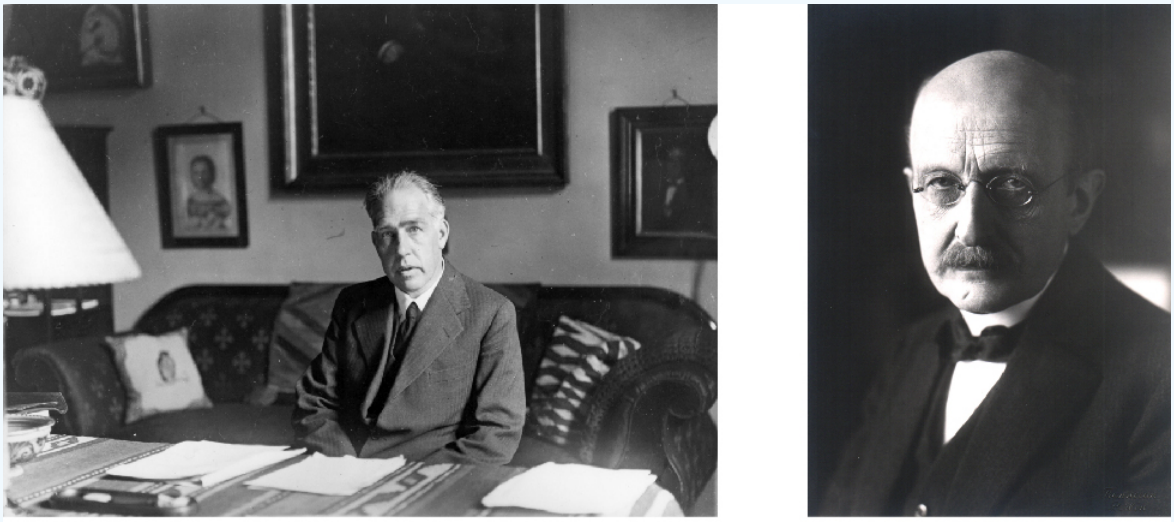
Here we have one of the situations where it is easier to think of electromagnetic radiation as particles (photons) rather than as waves. As electrons move from one level to another, they give off or absorb little packets of energy. When an electron moves to a higher level, it absorbs a photon of just the right energy (provided one is available). When it moves to a lower level, it emits a photon with the exact amount of energy it no longer needs in its "lower-cost living situation."

The photon and wave perspectives must be equivalent: light is light, no matter how we look at it. Thus, each photon carries a certain amount of energy that is proportional to the frequency (*f*) of the wave it represents. The value of its energy (*E*) is given by the formula

$$E = hf$$

where the constant of proportionality, *h*, is called Planck's constant.

The constant is named for Max Planck, the German physicist who was one of the originators of the quantum theory (Figure 5.18). If metric units are used (that is, if energy is measured in joules and frequency in hertz), then Planck's constant has the value $h = 6.626 \times 10^{-34}$ joule-seconds (J-s). Higher-energy photons correspond to higher-frequency waves (which have a shorter wavelength); lower-energy photons are waves of lower frequency.



(a) (b)

Figure 5.18 : Niels Bohr (1885–1962) and Max Planck (1858–1947). (a) Bohr, shown at his desk in this 1935 photograph, and (b) Planck helped us understand the energy behavior of photons.

To take a specific example, consider a calcium atom inside the Sun's atmosphere in which an electron jumps from a lower level to a higher level. To do this, it needs about 5×10^{-19} joules of energy, which it can conveniently obtain by absorbing a passing photon of that energy coming from deeper inside the Sun. This photon is equivalent to a wave of light whose frequency is about 7.5×10^{14} hertz and whose wavelength is about 3.9×10^{-7} meters (393 nanometers), in the deep violet part of the visible light spectrum. Although it may seem strange at first to switch from picturing light as a photon (or energy packet) to picturing it as a wave, such switching has become second nature to astronomers and can be a handy tool for doing calculations about spectra.

Example 5.5: The Energy of a Photon

Now that we know how to calculate the wavelength and frequency of a photon, we can use this information, along with Planck's constant, to determine how much energy each photon carries. How much energy does a red photon of wavelength 630 nm have?

Solution

First, as we learned earlier, we can find the frequency of the photon:

$$f = \frac{c}{\lambda} = \frac{3 \times 10^{8}\,\text{m/s}}{630 \times 10^{-9}\,\text{m}} = 4.8 \times 10^{14}\,\text{Hz}$$

Next, we can use Planck's constant to determine the energy (remember that a Hz is the same as 1/s):

$$E = hf = \left(6.626 \times 10^{-34}\,\text{J-s}\right)\left(4.8 \times 10^{14}\,\text{Hz}(1/\text{s})\right) = 3.2 \times 10^{-19}\,\text{J}$$

Exercise 5.5.1

What is the energy of a yellow photon with a frequency of 5.5×10^{14} Hz?

Answer

$$E = hf = \left(6.626 \times 10^{-34}\text{J-s}\right)\left(5.5 \times 10^{14}\text{Hz}\right) = 3.6 \times 10^{-19}\,\text{J}$$

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5.6: Formation of Spectral Lines

Learning Objectives

By the end of this section, you will be able to:

- Explain how emission line spectra and absorption line spectra are formed
- Describe what ions are and how they are formed
- Explain how spectral lines and ionization levels in a gas can help us determine its temperature

We can use Bohr's model of the atom to understand how spectral lines are formed. The concept of energy levels for the electron orbits in an atom leads naturally to an explanation of why atoms absorb or emit only specific energies or wavelengths of light.

The Hydrogen Spectrum

Let's look at the hydrogen atom from the perspective of the Bohr model. Suppose a beam of white light (which consists of photons of all visible wavelengths) shines through a gas of atomic hydrogen. A photon of wavelength 656 nanometers has just the right energy to raise an electron in a hydrogen atom from the second to the third orbit. Thus, as all the photons of different energies (or wavelengths or colors) stream by the hydrogen atoms, photons with *this* particular wavelength can be absorbed by those atoms whose electrons are orbiting on the second level. When they are absorbed, the electrons on the second level will move to the third level, and a number of the photons of this wavelength and energy will be missing from the general stream of white light.

Other photons will have the right energies to raise electrons from the second to the fourth orbit, or from the first to the fifth orbit, and so on. Only photons with these exact energies can be absorbed. All of the other photons will stream past the atoms untouched. Thus, hydrogen atoms absorb light at only certain wavelengths and produce dark lines at those wavelengths in the spectrum we see.

Suppose we have a container of hydrogen gas through which a whole series of photons is passing, allowing many electrons to move up to higher levels. When we turn off the light source, these electrons "fall" back down from larger to smaller orbits and emit photons of light—but, again, only light of those energies or wavelengths that correspond to the energy difference between permissible orbits. The orbital changes of hydrogen electrons that give rise to some spectral lines are shown in Figure 5.19.

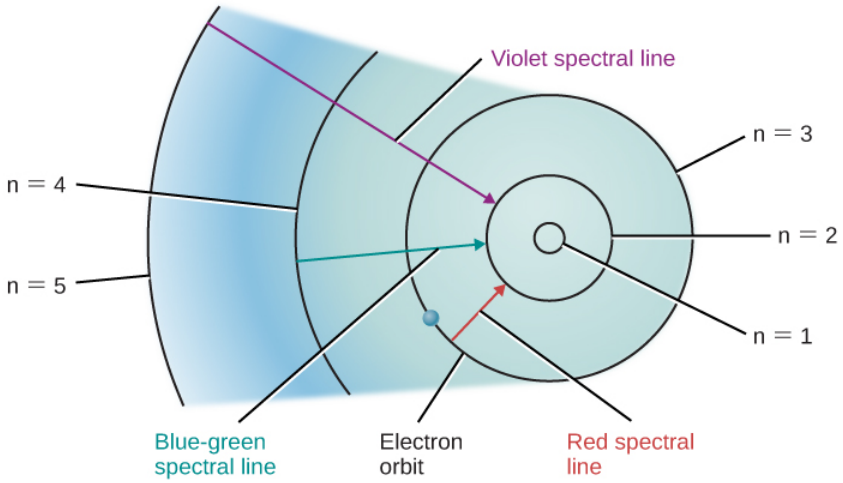


Figure 5.19 : Bohr Model for Hydrogen. In this simplified model of a hydrogen atom, the concentric circles shown represent permitted orbits or energy levels. An electron in a hydrogen atom can only exist in one of these energy levels (or states). The closer the electron is to the nucleus, the more tightly bound the electron is to the nucleus. By absorbing energy, the electron can move to energy levels farther from the nucleus (and even escape if enough energy is absorbed).

Similar pictures can be drawn for atoms other than hydrogen. However, because these other atoms ordinarily have more than one electron each, the orbits of their electrons are much more complicated, and the spectra are more complex as well. For our purposes, the key conclusion is this: *each type of atom has its own unique pattern of electron orbits, and no two sets of orbits are exactly alike*. This means that each type of atom shows its own unique set of spectral lines, produced by electrons moving between its unique set of orbits.

Astronomers and physicists have worked hard to learn the lines that go with each element by studying the way atoms absorb and emit light in laboratories here on Earth. Then they can use this knowledge to identify the elements in celestial bodies. In this way, we now know the chemical makeup of not just any star, but even galaxies of stars so distant that their light started on its way to us long before Earth had even formed.

Energy Levels and Excitation

Bohr's model of the hydrogen atom was a great step forward in our understanding of the atom. However, we know today that atoms cannot be represented by quite so simple a picture. For example, the concept of sharply defined electron orbits is not really correct; however, at the level of this introductory course, the notion that only certain discrete energies are allowable for an atom is very useful. The energy levels we have been discussing can be thought of as representing certain average distances of the electron's possible orbits from the atomic nucleus.

Ordinarily, an atom is in the state of lowest possible energy, its ground state. In the Bohr model of the hydrogen atom, the ground state corresponds to the electron being in the innermost orbit. An atom can absorb energy, which raises it to a higher energy level (corresponding, in the simple Bohr picture, to an electron's movement to a larger orbit)—this is referred to as excitation. The atom is then said to be in an *excited state*. Generally, an atom remains excited for only a very brief time. After a short interval, typically a hundred-millionth of a second or so, it drops back spontaneously to its ground state, with the simultaneous emission of light. The atom may return to its lowest state in one jump, or it may make the transition in steps of two or more jumps, stopping at intermediate levels on the way down. With each jump, it emits a photon of the wavelength that corresponds to the energy difference between the levels at the beginning and end of that jump.

An energy-level diagram for a hydrogen atom and several possible atomic transitions are shown in Figure 5.20. When we measure the energies involved as the atom jumps between levels, we find that the transitions to or from the ground state, called the *Lyman series* of lines, result in the emission or absorption of ultraviolet photons. But the transitions to or from the first excited state (labeled n = 2 in part (a) of Figure 5.20), called the Balmer series, produce emission or absorption in visible light. In fact, it was to explain this Balmer series that Bohr first suggested his model of the atom.

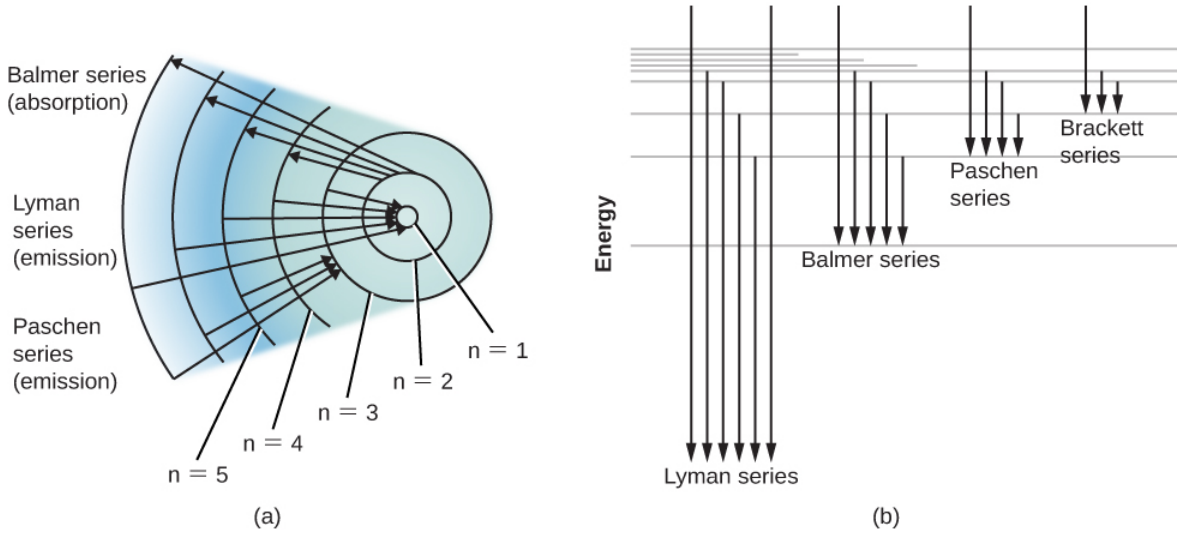


Figure 5.20 : Energy-Level Diagrams for Hydrogen. (a) Here we follow the emission or absorption of photons by a hydrogen atom according to the Bohr model. Several different series of spectral lines are shown, corresponding to transitions of electrons from or to certain allowed orbits. Each series of lines that terminates on a specific inner orbit is named for the physicist who studied it. At the top, for example, you see the Balmer series, and arrows show electrons jumping from the second orbit (n = 2) to the third, fourth, fifth, and sixth orbits. Each time a "poor" electron from a lower level wants to rise to a higher position in life, it must absorb energy to do so. It can absorb the energy it needs from passing waves (or photons) of light. The next set of arrows (Lyman series) show electrons falling down to the first orbit from different (higher) levels. Each time a "rich" electron goes downward toward the nucleus, it can afford to give off (emit) some energy it no longer needs. (In this idealized diagram, the energy levels are shown equally spaced; in real life, they are not.) (b) At higher and higher energy levels, the levels become more and more crowded together, approaching a limit. The region above the top line represents energies at which the atom is ionized (the electron is no longer attached to the atom). Each series of arrows represents electrons falling from higher levels to lower ones, releasing photons or waves of energy in the process.

Atoms that have absorbed specific photons from a passing beam of white light and have thus become excited generally de-excite themselves and emit that light again in a very short time. You might wonder, then, why *dark* spectral lines are ever produced. In

other words, why doesn't this reemitted light quickly "fill in" the darker absorption lines?

Imagine a beam of white light coming toward you through some cooler gas. Some of the reemitted light *is* actually returned to the beam of white light you see, but this fills in the absorption lines only to a slight extent. The reason is that the atoms in the gas reemit light *in all directions*, and only a small fraction of the reemitted light is in the direction of the original beam (toward you). In a star, much of the reemitted light actually goes in directions leading back into the star, which does observers outside the star no good whatsoever.

Figure 5.21 summarizes the different kinds of spectra we have discussed. An incandescent lightbulb produces a continuous spectrum. When that continuous spectrum is viewed through a thinner cloud of gas, an absorption line spectrum can be seen superimposed on the continuous spectrum. If we look only at a cloud of excited gas atoms (with no continuous source seen behind it), we see that the excited atoms give off an emission line spectrum.

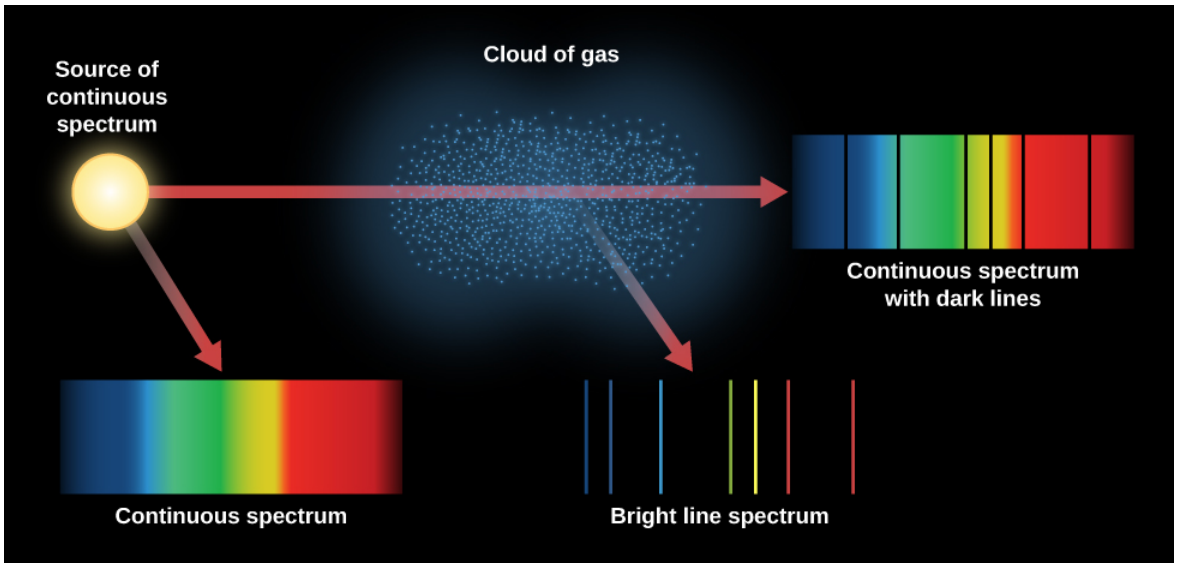


Figure 5.21 : Three Kinds of Spectra. When we see a lightbulb or other source of continuous radiation, all the colors are present. When the continuous spectrum is seen through a thinner gas cloud, the cloud's atoms produce absorption lines in the continuous spectrum. When the excited cloud is seen without the continuous source behind it, its atoms produce emission lines. We can learn which types of atoms are in the gas cloud from the pattern of absorption or emission lines.

Atoms in a hot gas are moving at high speeds and continually colliding with one another and with any loose electrons. They can be excited (electrons moving to a higher level) and de-excited (electrons moving to a lower level) by these collisions as well as by absorbing and emitting light. The speed of atoms in a gas depends on the temperature. When the temperature is higher, so are the speed and energy of the collisions. The hotter the gas, therefore, the more likely that electrons will occupy the outermost orbits, which correspond to the highest energy levels. This means that the level where electrons *start* their upward jumps in a gas can serve as an indicator of how hot that gas is. In this way, the absorption lines in a spectrum give astronomers information about the temperature of the regions where the lines originate.

Link to Learning

Use this simulation to play with a hydrogen atom and see what happens when electrons move to higher levels and then give off photons as they go to a lower level.

Ionization

We have described how certain discrete amounts of energy can be absorbed by an atom, raising it to an excited state and moving one of its electrons farther from its nucleus. If enough energy is absorbed, the electron can be completely removed from the atom—this is called ionization. The atom is then said to be ionized. The minimum amount of energy required to remove one electron from an atom in its ground state is called its ionization energy.

Still-greater amounts of energy must be absorbed by the now-ionized atom (called an ion) to remove an additional electron deeper in the structure of the atom. Successively greater energies are needed to remove the third, fourth, fifth—and so on—electrons from the atom. If enough energy is available, an atom can become completely ionized, losing all of its electrons. A hydrogen atom,

having only one electron to lose, can be ionized only once; a helium atom can be ionized twice; and an oxygen atom up to eight times. When we examine regions of the cosmos where there is a great deal of energetic radiation, such as the neighborhoods where hot young stars have recently formed, we see a lot of ionization going on.

An atom that has become positively ionized has lost a negative charge—the missing electron—and thus is left with a net positive charge. It therefore exerts a strong attraction on any free electron. Eventually, one or more electrons will be captured and the atom will become neutral (or ionized to one less degree) again. During the electron-capture process, the atom emits one or more photons. Which photons are emitted depends on whether the electron is captured at once to the lowest energy level of the atom or stops at one or more intermediate levels on its way to the lowest available level.

Just as the excitation of an atom can result from a collision with another atom, ion, or electron (collisions with electrons are usually most important), so can ionization. The rate at which such collisional ionizations occur depends on the speeds of the atoms and hence on the temperature of the gas—the hotter the gas, the more of its atoms will be ionized.

The rate at which ions and electrons recombine also depends on their relative speeds—that is, on the temperature. In addition, it depends on the density of the gas: the higher the density, the greater the chance for recapture, because the different kinds of particles are crowded more closely together. From a knowledge of the temperature and density of a gas, it is possible to calculate the fraction of atoms that have been ionized once, twice, and so on. In the Sun, for example, we find that most of the hydrogen and helium atoms in its atmosphere are neutral, whereas most of the calcium atoms, as well as many other heavier atoms, are ionized once.

The energy levels of an ionized atom are entirely different from those of the same atom when it is neutral. Each time an electron is removed from the atom, the energy levels of the ion, and thus the wavelengths of the spectral lines it can produce, change. This helps astronomers differentiate the ions of a given element. Ionized hydrogen, having no electron, can produce no absorption lines.

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5.7: The Doppler Effect

Learning Objectives

By the end of this section, you will be able to:

- Explain why the spectral lines of photons we observe from an object will change as a result of the object's motion toward or away from us
- Describe how we can use the Doppler effect to deduce how fast astronomical objects are moving through space

The last two sections introduced you to many new concepts, and we hope that through those, you have seen one major idea emerge. Astronomers can learn about the elements in stars and galaxies by decoding the information in their spectral lines. There is a complicating factor in learning how to decode the message of starlight, however. If a star is moving toward or away from us, its lines will be in a slightly different place in the spectrum from where they would be in a star at rest. And most objects in the universe do have some motion relative to the Sun.

Motion Affects Waves

In 1842, Christian Doppler first measured the effect of motion on waves by hiring a group of musicians to play on an open railroad car as it was moving along the track. He then applied what he learned to all waves, including light, and pointed out that if a light source is approaching or receding from the observer, the light waves will be, respectively, crowded more closely together or spread out. The general principle, now known as the Doppler effect, is illustrated in Figure 5.22.

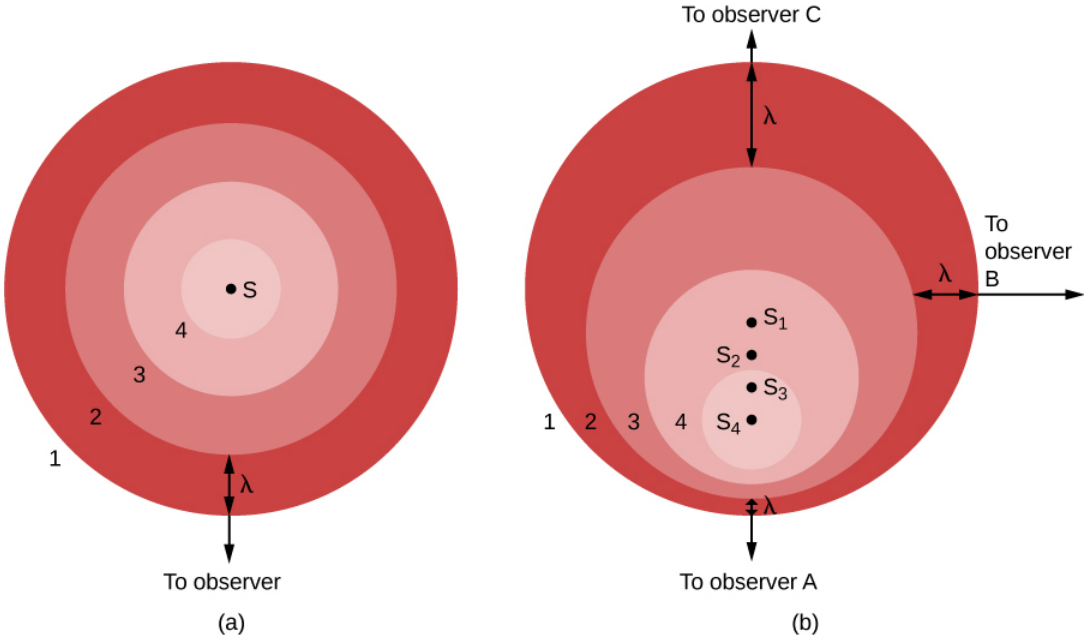


Figure 5.22 : Doppler Effect. (a) A source, S, makes waves whose numbered crests (1, 2, 3, and 4) wash over a stationary observer. (b) The source S now moves toward observer *A* and away from observer *C*. Wave crest 1 was emitted when the source was at position S1, crest 2 at position S2, and so forth. Observer *A* sees waves compressed by this motion and sees a blueshift (if the waves are light). Observer *C* sees the waves stretched out by the motion and sees a redshift. Observer *B*, whose line of sight is perpendicular to the source's motion, sees no change in the waves (and feels left out).

In part (a) of the figure, the light source (S) is at rest with respect to the observer. The source gives off a series of waves, whose crests we have labeled 1, 2, 3, and 4. The light waves spread out evenly in all directions, like the ripples from a splash in a pond. The crests are separated by a distance, λ, where λ is the wavelength. The observer, who happens to be located in the direction of the bottom of the image, sees the light waves coming nice and evenly, one wavelength apart. Observers located anywhere else would see the same thing.

On the other hand, if the source of light is moving with respect to the observer, as seen in part (b), the situation is more complicated. Between the time one crest is emitted and the next one is ready to come out, the source has moved a bit, toward the

bottom of the page. From the point of view of observer *A*, this motion of the source has decreased the distance between crests—it's squeezing the crests together, this observer might say.

In part (b), we show the situation from the perspective of three observers. The source is seen in four positions, S_1, S_2, S_3, and S_4, each corresponding to the emission of one wave crest. To observer *A*, the waves seem to follow one another more closely, at a decreased wavelength and thus increased frequency. (Remember, all light waves travel at the speed of light through empty space, no matter what. This means that motion cannot affect the speed, but only the wavelength and the frequency. As the wavelength decreases, the frequency must increase. If the waves are shorter, more will be able to move by during each second.)

The situation is not the same for other observers. Let's look at the situation from the point of view of observer *C*, located opposite observer *A* in the figure. For her, the source is moving away from her location. As a result, the waves are not squeezed together but instead are spread out by the motion of the source. The crests arrive with an increased wavelength and decreased frequency. To observer *B*, in a direction at right angles to the motion of the source, no effect is observed. The wavelength and frequency remain the same as they were in part (a) of the figure.

We can see from this illustration that the Doppler effect is produced only by a motion toward or away from the observer, a motion called radial velocity. Sideways motion does not produce such an effect. Observers between *A* and *B* would observe some shortening of the light waves for that part of the motion of the source that is along their line of sight. Observers between *B* and *C* would observe lengthening of the light waves that are along their line of sight.

You may have heard the Doppler effect with sound waves. When a train whistle or police siren approaches you and then moves away, you will notice a decrease in the pitch (which is how human senses interpret sound wave frequency) of the sound waves. Compared to the waves at rest, they have changed from slightly more frequent when coming toward you, to slightly less frequent when moving away from you.

Link to Learning

A nice example of this change in the sound of a train whistle can be heard at the end of the classic Beach Boys song "Caroline, No" on their album *Pet Sounds*. To hear this sound, go to this YouTube version of the song. The sound of the train begins at approximately 2:20.

Color Shifts

When the source of waves moves toward you, the wavelength decreases a bit. If the waves involved are visible light, then the colors of the light change slightly. As wavelength decreases, they shift toward the blue end of the spectrum: astronomers call this a *blueshift* (since the end of the spectrum is really violet, the term should probably be *violetshift*, but blue is a more common color). When the source moves away from you and the wavelength gets longer, we call the change in colors a *redshift*. Because the Doppler effect was first used with visible light in astronomy, the terms "blueshift" and "redshift" became well established. Today, astronomers use these words to describe changes in the wavelengths of radio waves or X-rays as comfortably as they use them to describe changes in visible light.

The greater the motion toward or away from us, the greater the Doppler shift. If the relative motion is entirely along the line of sight, the formula for the Doppler shift of light is

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

where λ is the wavelength emitted by the source, Δλ is the difference between λ and the wavelength measured by the observer, c is the speed of light, and v is the relative speed of the observer and the source in the line of sight. The variable v is counted as positive if the velocity is one of recession, and negative if it is one of approach. Solving this equation for the velocity, we find $v = c \times \Delta\lambda/\lambda$.

Link to Learning

Click-and-drag the object emitting waves or the object receiving waves in this simulator to experiment with the Doppler effect yourself. The plots along the top show how the detected wavelengths change if the objects are approaching each other or moving further apart.

If a star approaches or recedes from us, the wavelengths of light in its continuous spectrum appear shortened or lengthened, respectively, as do those of the dark lines. However, unless its speed is tens of thousands of kilometers per second, the star does not appear noticeably bluer or redder than normal. The Doppler shift is thus not easily detected in a continuous spectrum and cannot be measured accurately in such a spectrum. The wavelengths of the absorption lines can be measured accurately, however, and their Doppler shift is relatively simple to detect.

Example 5.6: The Doppler Effect

We can use the Doppler effect equation to calculate the radial velocity of an object if we know three things: the speed of light, the original (unshifted) wavelength of the light emitted, and the difference between the wavelength of the emitted light and the wavelength we observe. For particular absorption or emission lines, we usually know exactly what wavelength the line has in our laboratories on Earth, where the source of light is not moving. We can measure the new wavelength with our instruments at the telescope, and so we know the difference in wavelength due to Doppler shifting. Since the speed of light is a universal constant, we can then calculate the radial velocity of the star.

A particular emission line of hydrogen is originally emitted with a wavelength of 656.3 nm from a gas cloud. At our telescope, we observe the wavelength of the emission line to be 656.6 nm. How fast is this gas cloud moving toward or away from Earth?

Solution

Because the light is shifted to a longer wavelength (redshifted), we know this gas cloud is moving away from us. The speed can be calculated using the Doppler shift formula:

$$\begin{aligned} \nu &= c \times \frac{\Delta\lambda}{\lambda} = \left(3.0 \times 10^8 \text{ m/s}\right)\left(\frac{0.3 \text{ nm}}{656.3 \text{ nm}}\right) = \left(3.0 \times 10^8 \text{ m/s}\right)\left(\frac{0.3 \times 10^{-9} \text{ m}}{656.3 \times 10^{-9} \text{ m}}\right) \\ &= 140{,}000 \text{ m/s} = 140 \text{ km/s} \end{aligned}$$

Exercise 5.7.1

Suppose a spectral line of hydrogen, normally at 500 nm, is observed in the spectrum of a star to be at 500.1 nm. How fast is the star moving toward or away from Earth?

Answer

Because the light is shifted to a longer wavelength, the star is moving away from us:

$\nu = c \times \frac{\Delta\lambda}{\lambda} = \left(3.0 \times 10^8 \text{ m/s}\right)\left(\frac{0.1 \text{ nm}}{500 \text{ nm}}\right) = \left(3.0 \times 10^8 \text{ m/s}\right)\left(\frac{0.1 \times 10^{-9} \text{ m}}{500 \times 10^{-9} \text{ m}}\right) = 60{,}000 \text{ m/s}$. Its speed is 60,000 m/s.

You may now be asking: if all the stars are moving and motion changes the wavelength of each spectral line, won't this be a disaster for astronomers trying to figure out what elements are present in the stars? After all, it is the precise wavelength (or color) that tells astronomers which lines belong to which element. And we first measure these wavelengths in containers of gas in our laboratories, which are not moving. If every line in a star's spectrum is now shifted by its motion to a different wavelength (color), how can we be sure which lines and which elements we are looking at in a star whose speed we do not know?

Take heart. This situation sounds worse than it really is. Astronomers rarely judge the presence of an element in an astronomical object by a single line. It is the *pattern* of lines unique to hydrogen or calcium that enables us to determine that those elements are part of the star or galaxy we are observing. The Doppler effect does not change the pattern of lines from a given element—it only shifts the whole pattern slightly toward redder or bluer wavelengths. The shifted pattern is still quite easy to recognize. Best of all, when we do recognize a familiar element's pattern, we get a bonus: the amount the pattern is shifted can enable us to determine the speed of the objects in our line of sight.

The training of astronomers includes much work on learning to decode light (and other electromagnetic radiation). A skillful "decoder" can learn the temperature of a star, what elements are in it, and even its speed in a direction toward us or away from us. That's really an impressive amount of information for stars that are light-years away.

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5.8: Key Terms

absorption spectrum
a series or pattern of dark lines superimposed on a continuous spectrum

blackbody
an idealized object that absorbs all electromagnetic energy that falls onto it

continuous spectrum
a spectrum of light composed of radiation of a continuous range of wavelengths or colors, rather than only certain discrete wavelengths

dispersion
separation of different wavelengths of white light through refraction of different amounts

Doppler effect
the apparent change in wavelength or frequency of the radiation from a source due to its relative motion away from or toward the observer

electromagnetic radiation
radiation consisting of waves propagated through regularly varying electric and magnetic fields and traveling at the speed of light

electromagnetic spectrum
the whole array or family of electromagnetic waves, from radio to gamma rays

emission spectrum
a series or pattern of bright lines superimposed on a continuous spectrum

energy flux
the amount of energy passing through a unit area (for example, 1 square meter) per second; the units of flux are watts per square meter

energy level
a particular level, or amount, of energy possessed by an atom or ion above the energy it possesses in its least energetic state; also used to refer to the states of energy an electron can have in an atom

excitation
the process of giving an atom or an ion an amount of energy greater than it has in its lowest energy (ground) state

frequency
the number of waves that cross a given point per unit time (in radiation)

gamma rays
photons (of electromagnetic radiation) of energy with wavelengths no longer than 0.01 nanometer; the most energetic form of electromagnetic radiation

ground state
the lowest energy state of an atom

infrared
electromagnetic radiation of wavelength 10^3–10^6 nanometers; longer than the longest (red) wavelengths that can be perceived by the eye, but shorter than radio wavelengths

inverse square law

(for light) the amount of energy (light) flowing through a given area in a given time decreases in proportion to the square of the distance from the source of energy or light

ion
an atom that has become electrically charged by the addition or loss of one or more electrons

ionization
the process by which an atom gains or loses electrons

isotope
any of two or more forms of the same element whose atoms have the same number of protons but different numbers of neutrons

microwave
electromagnetic radiation of wavelengths from 1 millimeter to 1 meter; longer than infrared but shorter than radio waves

nucleus (of an atom)
the massive part of an atom, composed mostly of protons and neutrons, and about which the electrons revolve

photon
a discrete unit (or “packet”) of electromagnetic energy

radial velocity
motion toward or away from the observer; the component of relative velocity that lies in the line of sight

radio waves
all electromagnetic waves longer than microwaves, including radar waves and AM radio waves

spectrometer
an instrument for obtaining a spectrum; in astronomy, usually attached to a telescope to record the spectrum of a star, galaxy, or other astronomical object

Stefan-Boltzmann law
a formula from which the rate at which a blackbody radiates energy can be computed; the total rate of energy emission from a unit area of a blackbody is proportional to the fourth power of its absolute temperature: $F = \sigma T^4$

ultraviolet
electromagnetic radiation of wavelengths 10 to 400 nanometers; shorter than the shortest visible wavelengths

visible light
electromagnetic radiation with wavelengths of roughly 400–700 nanometers; visible to the human eye

wavelength
the distance from crest to crest or trough to trough in a wave

Wien’s law
formula that relates the temperature of a blackbody to the wavelength at which it emits the greatest intensity of radiation

X-rays
electromagnetic radiation with wavelengths between 0.01 nanometer and 20 nanometers; intermediate between those of ultraviolet radiation and gamma rays

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5.9: Summary

5.1 The Behavior of Light

James Clerk Maxwell showed that whenever charged particles change their motion, as they do in every atom and molecule, they give off waves of energy. Light is one form of this electromagnetic radiation. The wavelength of light determines the color of visible radiation. Wavelength (λ) is related to frequency (*f*) and the speed of light (*c*) by the equation $c = \lambda f$. Electromagnetic radiation sometimes behaves like waves, but at other times, it behaves as if it were a particle—a little packet of energy, called a photon. The apparent brightness of a source of electromagnetic energy decreases with increasing distance from that source in proportion to the square of the distance—a relationship known as the inverse square law.

5.2 The Electromagnetic Spectrum

The electromagnetic spectrum consists of gamma rays, X-rays, ultraviolet radiation, visible light, infrared, and radio radiation. Many of these wavelengths cannot penetrate the layers of Earth's atmosphere and must be observed from space, whereas others—such as visible light, FM radio and TV—can penetrate to Earth's surface. The emission of electromagnetic radiation is intimately connected to the temperature of the source. The higher the temperature of an idealized emitter of electromagnetic radiation, the shorter is the wavelength at which the maximum amount of radiation is emitted. The mathematical equation describing this relationship is known as Wien's law: $\lambda_{\text{max}} = \frac{(3\times10^{6})}{}$. The total power emitted per square meter increases with increasing temperature. The relationship between emitted energy flux and temperature is known as the Stefan-Boltzmann law: $F =$.

5.3 Spectroscopy in Astronomy

A spectrometer is a device that forms a spectrum, often utilizing the phenomenon of dispersion. The light from an astronomical source can consist of a continuous spectrum, an emission (bright line) spectrum, or an absorption (dark line) spectrum. Because each element leaves its spectral signature in the pattern of lines we observe, spectral analyses reveal the composition of the Sun and stars.

5.4 The Structure of the Atom

Atoms consist of a nucleus containing one or more positively charged protons. All atoms except hydrogen can also contain one or more neutrons in the nucleus. Negatively charged electrons orbit the nucleus. The number of protons defines an element (hydrogen has one proton, helium has two, and so on) of the atom. Nuclei with the same number of protons but different numbers of neutrons are different isotopes of the same element. In the Bohr model of the atom, electrons on permitted orbits (or energy levels) don't give off any electromagnetic radiation. But when electrons go from lower levels to higher ones, they must absorb a photon of just the right energy, and when they go from higher levels to lower ones, they give off a photon of just the right energy. The energy of a photon is connected to the frequency of the electromagnetic wave it represents by Planck's formula, $E = hf$.

5.5 Formation of Spectral Lines

When electrons move from a higher energy level to a lower one, photons are emitted, and an emission line can be seen in the spectrum. Absorption lines are seen when electrons absorb photons and move to higher energy levels. Since each atom has its own characteristic set of energy levels, each is associated with a unique pattern of spectral lines. This allows astronomers to determine what elements are present in the stars and in the clouds of gas and dust among the stars. An atom in its lowest energy level is in the ground state. If an electron is in an orbit other than the least energetic one possible, the atom is said to be excited. If an atom has lost one or more electrons, it is called an ion and is said to be ionized. The spectra of different ions look different and can tell astronomers about the temperatures of the sources they are observing.

5.6 The Doppler Effect

If an atom is moving toward us when an electron changes orbits and produces a spectral line, we see that line shifted slightly toward the blue of its normal wavelength in a spectrum. If the atom is moving away, we see the line shifted toward the red. This shift is known as the Doppler effect and can be used to measure the radial velocities of distant objects.

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5.10: For Further Exploration

Articles

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Electromagnetic Spectrum: http://imagine.gsfc.nasa.gov/science/toolbox/emspectrum1.html. An introduction to the electromagnetic spectrum from NASA’s *Imagine the Universe*; note that you can click the “Advanced” button near the top and get a more detailed discussion.

Rainbows: How They Form and How to See Them: http://www.livescience.com/30235-rainbows-formation-explainer.html. By meteorologist and amateur astronomer Joe Rao.

Videos

Doppler Effect: http://www.esa.int/spaceinvideos/Videos/2014/07/Doppler_effect_-_classroom_demonstration_video_VP05. ESA video with Doppler ball demonstration and Doppler effect and satellites (4:48).

How a Prism Works to Make Rainbow Colors: https://www.youtube.com/watch?v=JGqsi_LDUn0. Short video on how a prism bends light to make a rainbow of colors (2:44).

Tour of the Electromagnetic Spectrum: https://www.youtube.com/watch?v=HPcAWNlVl-8. *NASA Mission Science* video tour of the bands of the electromagnetic spectrum (eight short videos).

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5.11: Collaborative Group Activities

A. Have your group make a list of all the electromagnetic wave technology you use during a typical day.
B. How many applications of the Doppler effect can your group think of in everyday life? For example, why would the highway patrol find it useful?
C. Have members of your group go home and “read” the face of your radio set and then compare notes. If you do not have a radio, research “broadcast radio frequencies” to find answers to the following questions. What do all the words and symbols mean? What frequencies can your radio tune to? What is the frequency of your favorite radio station? What is its wavelength?
D. If your instructor were to give you a spectrometer, what kind of spectra does your group think you would see from each of the following: (1) a household lightbulb, (2) the Sun, (3) the “neon lights of Broadway,” (4) an ordinary household flashlight, and (5) a streetlight on a busy shopping street?
E. Suppose astronomers want to send a message to an alien civilization that is living on a planet with an atmosphere very similar to that of Earth’s. This message must travel through space, make it through the other planet’s atmosphere, and be noticeable to the residents of that planet. Have your group discuss what band of the electromagnetic spectrum might be best for this message and why. (Some people, including noted physicist Stephen Hawking, have warned scientists not to send such messages and reveal the presence of our civilization to a possible hostile cosmos. Do you agree with this concern?)

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CHAPTER OVERVIEW

5.12: Exercises

5.12.1: Review Questions

5.12.2: Thought Questions

5.12.3: Figuring for Yourself

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5.12.1: Review Questions

Review Questions

1.

What distinguishes one type of electromagnetic radiation from another? What are the main categories (or bands) of the electromagnetic spectrum?

2.

What is a wave? Use the terms *wavelength* and *frequency* in your definition.

3.

Is your textbook the kind of idealized object (described in section on radiation laws) that absorbs all the radiation falling on it? Explain. How about the black sweater worn by one of your classmates?

4.

Where in an atom would you expect to find electrons? Protons? Neutrons?

5.

Explain how emission lines and absorption lines are formed. In what sorts of cosmic objects would you expect to see each?

6.

Explain how the Doppler effect works for sound waves and give some familiar examples.

7.

What kind of motion for a star does not produce a Doppler effect? Explain.

8.

Describe how Bohr’s model used the work of Maxwell.

9.

Explain why light is referred to as electromagnetic radiation.

10.

Explain the difference between radiation as it is used in most everyday language and radiation as it is used in an astronomical context.

11.

What are the differences between light waves and sound waves?

12.

Which type of wave has a longer wavelength: AM radio waves (with frequencies in the kilohertz range) or FM radio waves (with frequencies in the megahertz range)? Explain.

13.

Explain why astronomers long ago believed that space must be filled with some kind of substance (the “aether”) instead of the vacuum we know it is today.

14.

Explain what the ionosphere is and how it interacts with some radio waves.

15.

Which is more dangerous to living things, gamma rays or X-rays? Explain.

16.

Explain why we have to observe stars and other astronomical objects from above Earth's atmosphere in order to fully learn about their properties.

17.

Explain why hotter objects tend to radiate more energetic photons compared to cooler objects.

18.

Explain how we can deduce the temperature of a star by determining its color.

19.

Explain what dispersion is and how astronomers use this phenomenon to study a star's light.

20.

Explain why glass prisms disperse light.

21.

Explain what Joseph Fraunhofer discovered about stellar spectra.

22.

Explain how we use spectral absorption and emission lines to determine the composition of a gas.

23.

Explain the results of Rutherford's gold foil experiment and how they changed our model of the atom.

24.

Is it possible for two different atoms of carbon to have different numbers of neutrons in their nuclei? Explain.

25.

What are the three isotopes of hydrogen, and how do they differ?

26.

Explain how electrons use light energy to move among energy levels within an atom.

27.

Explain why astronomers use the term "blueshifted" for objects moving toward us and "redshifted" for objects moving away from us.

28.

If spectral line wavelengths are changing for objects based on the radial velocities of those objects, how can we deduce which type of atom is responsible for a particular absorption or emission line?

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5.12.2: Thought Questions

Thought Questions

29.

Make a list of some of the many practical consequences of Maxwell's theory of electromagnetic waves (television is one example).

30.

With what type of electromagnetic radiation would you observe:

A. A star with a temperature of 5800 K?
B. A gas heated to a temperature of one million K?
C. A person on a dark night?

31.

Why is it dangerous to be exposed to X-rays but not (or at least much less) dangerous to be exposed to radio waves?

32.

Go outside on a clear night, wait 15 minutes for your eyes to adjust to the dark, and look carefully at the brightest stars. Some should look slightly red and others slightly blue. The primary factor that determines the color of a star is its temperature. Which is hotter: a blue star or a red one? Explain

33.

Water faucets are often labeled with a red dot for hot water and a blue dot for cold. Given Wien's law, does this labeling make sense?

34.

Suppose you are standing at the exact center of a park surrounded by a circular road. An ambulance drives completely around this road, with siren blaring. How does the pitch of the siren change as it circles around you?

35.

How could you measure Earth's orbital speed by photographing the spectrum of a star at various times throughout the year? (Hint: Suppose the star lies in the plane of Earth's orbit.)

36.

Astronomers want to make maps of the sky showing sources of X-rays or gamma rays. Explain why those X-rays and gamma rays must be observed from above Earth's atmosphere.

37.

The greenhouse effect can be explained easily if you understand the laws of blackbody radiation. A greenhouse gas blocks the transmission of infrared light. Given that the incoming light to Earth is sunlight with a characteristic temperature of 5800 K (which peaks in the visible part of the spectrum) and the outgoing light from Earth has a characteristic temperature of about 300 K (which peaks in the infrared part of the spectrum), explain how greenhouse gases cause Earth to warm up. As part of your answer, discuss that greenhouse gases block both incoming and outgoing infrared light. Explain why these two effects don't simply cancel each other, leading to no net temperature change.

38.

An idealized radiating object does not reflect or scatter any radiation but instead absorbs all of the electromagnetic energy that falls on it. Can you explain why astronomers call such an object a blackbody? Keep in mind that even stars, which shine brightly in a variety of colors, are considered blackbodies. Explain why.

39.

Why are ionized gases typically only found in very high-temperature environments?

40.

Explain why each element has a unique spectrum of absorption or emission lines.

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5.12.3: Figuring for Yourself

Figuring for Yourself

41.

What is the wavelength of the carrier wave of a campus radio station, broadcasting at a frequency of 97.2 MHz (million cycles per second or million hertz)?

42.

What is the frequency of a red laser beam, with a wavelength of 670 nm, which your astronomy instructor might use to point to slides during a lecture on galaxies?

43.

You go to a dance club to forget how hard your astronomy midterm was. What is the frequency of a wave of ultraviolet light coming from a blacklight in the club, if its wavelength is 150 nm?

44.

What is the energy of the photon with the frequency you calculated in Exercise 5.43?

45.

If the emitted infrared radiation from Pluto, has a wavelength of maximum intensity at 75,000 nm, what is the temperature of Pluto assuming it follows Wien's law?

46.

What is the temperature of a star whose maximum light is emitted at a wavelength of 290 nm?

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CHAPTER OVERVIEW

6: Astronomical Instruments

If you look at the sky when you are far away from city lights, there seem to be an overwhelming number of stars up there. In reality, only about 9000 stars are visible to the unaided eye (from both hemispheres of our planet). The light from most stars is so weak that by the time it reaches Earth, it cannot be detected by the human eye. How can we learn about the vast majority of objects in the universe that our unaided eyes simply cannot see?

In this chapter, we describe the tools astronomers use to extend their vision into space. We have learned almost everything we know about the universe from studying electromagnetic radiation, as discussed in the chapter on Radiation and Spectra. In the twentieth century, our exploration of space made it possible to detect electromagnetic radiation at all wavelengths, from gamma rays to radio waves. The different wavelengths carry different kinds of information, and the appearance of any given object often depends on the wavelength at which the observations are made.

6.1: Thinking Ahead
6.2: Telescopes
6.3: Telescopes Today
6.4: Visible-Light Detectors and Instruments
6.5: Radio Telescopes
6.6: Observations outside Earth's Atmosphere
6.7: The Future of Large Telescopes
6.8: Key Terms
6.9: Summary
6.10: For Further Exploration
6.11: Collaborative Group Activities
6.12: Exercises
6.12.1: Review Questions
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6.1: Thinking Ahead



Figure 6.1 : Hubble Space Telescope (HST). This artist's impression shows the Hubble above Earth, with the rectangular solar panels that provide it with power seen to the left and right.

If you look at the sky when you are far away from city lights, there seem to be an overwhelming number of stars up there. In reality, only about 9000 stars are visible to the unaided eye (from both hemispheres of our planet). The light from most stars is so weak that by the time it reaches Earth, it cannot be detected by the human eye. How can we learn about the vast majority of objects in the universe that our unaided eyes simply cannot see?

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6.2: Telescopes

Learning Objectives

By the end of this section, you will be able to:

- Describe the three basic components of a modern system for measuring astronomical sources
- Describe the main functions of a telescope
- Describe the two basic types of visible-light telescopes and how they form images

Systems for Measuring Radiation

There are three basic components of a modern system for measuring radiation from astronomical sources. First, there is a telescope, which serves as a "bucket" for collecting visible light (or radiation at other wavelengths, as shown in (Figure 6.2). Just as you can catch more rain with a garbage can than with a coffee cup, large telescopes gather much more light than your eye can. Second, there is an instrument attached to the telescope that sorts the incoming radiation by wavelength. Sometimes the sorting is fairly crude. For example, we might simply want to separate blue light from red light so that we can determine the temperature of a star. But at other times, we want to see individual spectral lines to determine what an object is made of, or to measure its speed (as explained in the Radiation and Spectra chapter). Third, we need some type of detector, a device that senses the radiation in the wavelength regions we have chosen and permanently records the observations.



Figure 6.2 : Orion Region at Different Wavelengths. The same part of the sky looks different when observed with instruments that are sensitive to different bands of the spectrum. (a) Visible light: this shows part of the Orion region as the human eye sees it, with dotted lines added to show the figure of the mythical hunter, Orion. (b) X-rays: here, the view emphasizes the point-like X-ray sources nearby. The colors are artificial, changing from yellow to white to blue with increasing energy of the X-rays. The bright, hot stars in Orion are still seen in this image, but so are many other objects located at very different distances, including other stars, star corpses, and galaxies at the edge of the observable universe. (c) Infrared radiation: here, we mainly see the glowing dust in this region. (credit a: modification of work by Howard McCallon/NASA/IRAS; credit b: modification of work by Howard McCallon/NASA/IRAS; credit c: modification of work by Michael F. Corcoran)

The history of the development of astronomical telescopes is about how new technologies have been applied to improve the efficiency of these three basic components: the telescopes, the wavelength-sorting device, and the detectors. Let's first look at the development of the telescope.

Many ancient cultures built special sites for observing the sky (Figure 6.3). At these ancient *observatories*, they could measure the positions of celestial objects, mostly to keep track of time and date. Many of these ancient observatories had religious and ritual functions as well. The eye was the only device available to gather light, all of the colors in the light were observed at once, and the only permanent record of the observations was made by human beings writing down or sketching what they saw.



(a) (b)

Figure 6.3 : Two Pre-Telescopic Observatories. (a) Machu Picchu is a fifteenth century Incan site located in Peru. (b) Stonehenge, a prehistoric site (3000–2000 BCE), is located in England. (credit a: modification of work by Allard Schmidt)

While Hans Lippershey, Zaccharias Janssen, and Jacob Metius are all credited with the invention of the telescope around 1608—applying for patents within weeks of each other—it was Galileo who, in 1610, used this simple tube with lenses (which he called a spyglass) to observe the sky and gather more light than his eyes alone could. Even his small telescope—used over many nights—revolutionized ideas about the nature of the planets and the position of Earth.

How Telescopes Work

Telescopes have come a long way since Galileo's time. Now they tend to be huge devices; the most expensive cost hundreds of millions to billions of dollars. (To provide some reference point, however, keep in mind that just renovating college football stadiums typically costs hundreds of millions of dollars—with the most expensive recent renovation, at Texas A&M University's Kyle Field, costing $450 million.) The reason astronomers keep building bigger and bigger telescopes is that celestial objects—such as planets, stars, and galaxies—send much more light to Earth than any human eye (with its tiny opening) can catch, and bigger telescopes can detect fainter objects. If you have ever watched the stars with a group of friends, you know that there's plenty of starlight to go around; each of you can see each of the stars. If a thousand more people were watching, each of them would also catch a bit of each star's light. Yet, as far as you are concerned, the light not shining into your eye is wasted. It would be great if some of this "wasted" light could also be captured and brought to your eye. This is precisely what a telescope does.

The most important functions of a telescope are (1) to *collect* the faint light from an astronomical source and (2) to *focus* all the light into a point or an image. Most objects of interest to astronomers are extremely faint: the more light we can collect, the better we can study such objects. (And remember, even though we are focusing on visible light first, there are many telescopes that collect other kinds of electromagnetic radiation.)

Telescopes that collect visible radiation use a lens or mirror to gather the light. Other types of telescopes may use collecting devices that look very different from the lenses and mirrors with which we are familiar, but they serve the same function. In all types of telescopes, the light-gathering ability is determined by the area of the device acting as the light-gathering "bucket." Since most telescopes have mirrors or lenses, we can compare their light-gathering power by comparing the apertures, or diameters, of the opening through which light travels or reflects.

The amount of light a telescope can collect increases with the size of the aperture. A telescope with a mirror that is 4 meters in diameter can collect 16 times as much light as a telescope that is 1 meter in diameter. (The diameter is squared because the area of a circle equals $\frac{\pi d^2}{4}$, where d is the diameter of the circle.)

Example 6.1: Calculating the Light-Collecting Area

What is the area of a 1-m diameter telescope? A 4-m diameter one?

Solution

Using the equation for the area of a circle,

$$A =$$

the area of a 1-m telescope is

$$\frac{\pi d^2}{4} = \frac{\pi(1\text{ m})^2}{4} = 0.79\text{ m}^2$$

and the area of a 4-m telescope is

$$\frac{\pi d^2}{4} = \frac{\pi(4\text{ m})^2}{4} = 12.6\text{ m}^2$$

Exercise 6.2.1

Show that the ratio of the two areas is 16:1.

Answer

$\frac{12.6\text{ m}^2}{0.79\text{ m}^2} = 16$. Therefore, with 16 times the area, a 4-m telescope collects 16 times the light of a 1-m telescope.

After the telescope forms an image, we need some way to detect and record it so that we can measure, reproduce, and analyze the image in various ways. Before the nineteenth century, astronomers simply viewed images with their eyes and wrote descriptions of what they saw. This was very inefficient and did not lead to a very reliable long-term record; you know from crime shows on television that eyewitness accounts are often inaccurate.

In the nineteenth century, the use of photography became widespread. In those days, photographs were a chemical record of an image on a specially treated glass plate. Today, the image is generally detected with sensors similar to those in digital cameras, recorded electronically, and stored in computers. This permanent record can then be used for detailed and quantitative studies. Professional astronomers rarely look through the large telescopes that they use for their research.

Formation of an Image by a Lens or a Mirror

Whether or not you wear glasses, you see the world through lenses; they are key elements of your eyes. A lens is a transparent piece of material that bends the rays of light passing through it. If the light rays are parallel as they enter, the lens brings them together in one place to form an image (Figure 6.4). If the curvatures of the lens surfaces are just right, all parallel rays of light (say, from a star) are bent, or *refracted*, in such a way that they converge toward a point, called the focus of the lens. At the focus, an image of the light source appears. In the case of parallel light rays, the distance from the lens to the location where the light rays focus, or image, behind the lens is called the *focal length* of the lens.

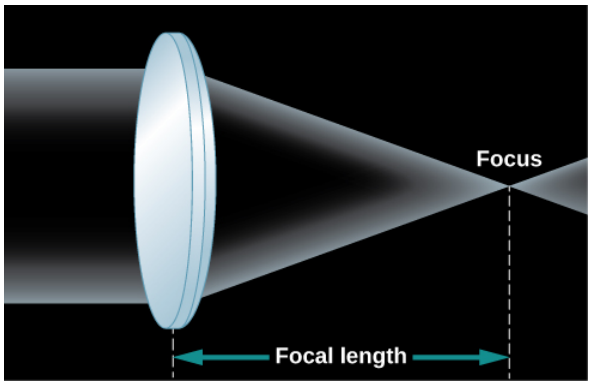


Figure 6.4 : Formation of an Image by a Simple Lens. Parallel rays from a distant source are bent by the convex lens so that they all come together in a single place (the focus) to form an image.

As you look at Figure 6.4, you may ask why two rays of light from the same star would be parallel to each other. After all, if you draw a picture of star shining in all directions, the rays of light coming from the star don't look parallel at all. But remember that the stars (and other astronomical objects) are all extremely far away. By the time the few rays of light pointed toward us actually arrive at Earth, they are, for all practical purposes, parallel to each other. Put another way, any rays that were *not* parallel to the ones pointed at Earth are now heading in some very different direction in the universe.

To view the image formed by the lens in a telescope, we use an additional lens called an eyepiece. The eyepiece focuses the image at a distance that is either directly viewable by a human or at a convenient place for a detector. Using different eyepieces, we can change the *magnification* (or size) of the image and also redirect the light to a more accessible location. Stars look like points of light, and magnifying them makes little difference, but the image of a planet or a galaxy, which has structure, can often benefit from being magnified.

Many people, when thinking of a telescope, picture a long tube with a large glass lens at one end. This design, which uses a lens as its main optical element to form an image, as we have been discussing, is known as a *refractor* (Figure 6.5), and a telescope based on this design is called a refracting telescope. Galileo's telescopes were refractors, as are today's binoculars and field glasses. However, there is a limit to the size of a refracting telescope. The largest one ever built was a 49-inch refractor built for the Paris 1900 Exposition, and it was dismantled after the Exposition. Currently, the largest refracting telescope is the 40-inch refractor at Yerkes Observatory in Wisconsin.

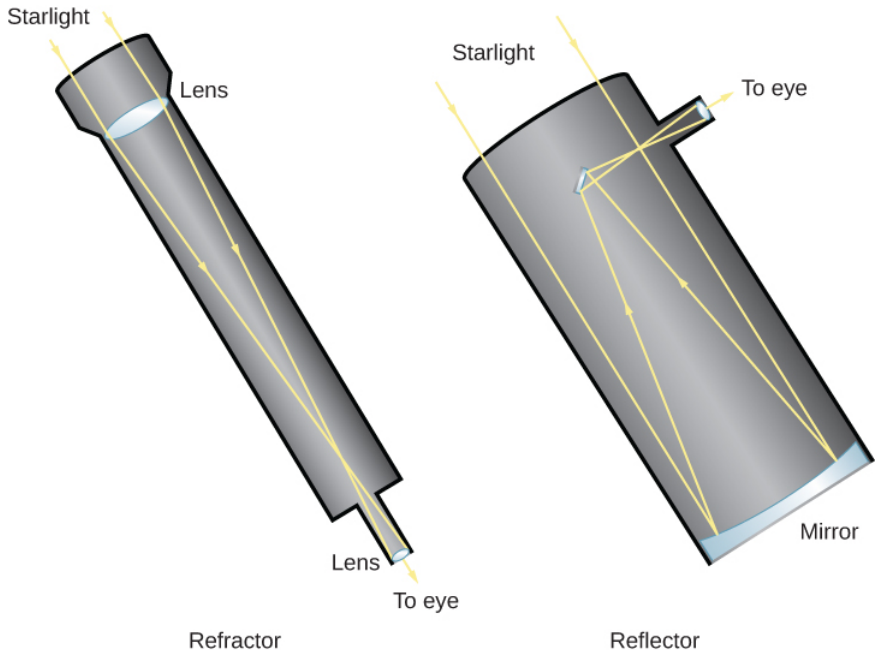


Figure 6.5 : Refracting and Reflecting Telescopes. Light enters a refracting telescope through a lens at the upper end, which focuses the light near the bottom of the telescope. An eyepiece then magnifies the image so that it can be viewed by the eye, or a detector like a photographic plate can be placed at the focus. The upper end of a reflecting telescope is open, and the light passes through to the mirror located at the bottom of the telescope. The mirror then focuses the light at the top end, where it can be detected. Alternatively, as in this sketch, a second mirror may reflect the light to a position outside the telescope structure, where an observer can have easier access to it. Professional astronomers' telescopes are more complicated than this, but they follow the same principles of reflection and refraction.

One problem with a refracting telescope is that the light must pass *through* the lens of a refractor. That means the glass must be perfect all the way through, and it has proven very difficult to make large pieces of glass without flaws and bubbles in them. Also, optical properties of transparent materials change a little bit with the wavelengths (or colors) of light, so there is some additional distortion, known as chromatic aberration. Each wavelength focuses at a slightly different spot, causing the image to appear blurry.

In addition, since the light must pass through the lens, the lens can only be supported around its edges (just like the frames of our eyeglasses). The force of gravity will cause a large lens to sag and distort the path of the light rays as they pass through it. Finally, because the light passes through it, both sides of the lens must be manufactured to precisely the right shape in order to produce a sharp image.

A different type of telescope uses a concave *primary mirror* as its main optical element. The mirror is curved like the inner surface of a sphere, and it reflects light in order to form an image (Figure 6.5). Telescope mirrors are coated with a shiny metal, usually silver, aluminum, or, occasionally, gold, to make them highly reflective. If the mirror has the correct shape, all parallel rays are reflected back to the same point, the focus of the mirror. Thus, images are produced by a mirror exactly as they are by a lens.

Telescopes designed with mirrors avoid the problems of refracting telescopes. Because the light is reflected from the front surface only, flaws and bubbles within the glass do not affect the path of the light. In a telescope designed with mirrors, only the front surface has to be manufactured to a precise shape, and the mirror can be supported from the back. For these reasons, most astronomical telescopes today (both amateur and professional) use a mirror rather than a lens to form an image; this type of telescope is called a reflecting telescope. The first successful reflecting telescope was built by Isaac Newton in 1668.

In a reflecting telescope, the concave mirror is placed at the bottom of a tube or open framework. The mirror reflects the light back up the tube to form an image near the front end at a location called the prime focus. The image can be observed at the prime focus, or additional mirrors can intercept the light and redirect it to a position where the observer can view it more easily (Figure 6.6). Since an astronomer at the prime focus can block much of the light coming to the main mirror, the use of a small *secondary mirror* allows more light to get through the system.

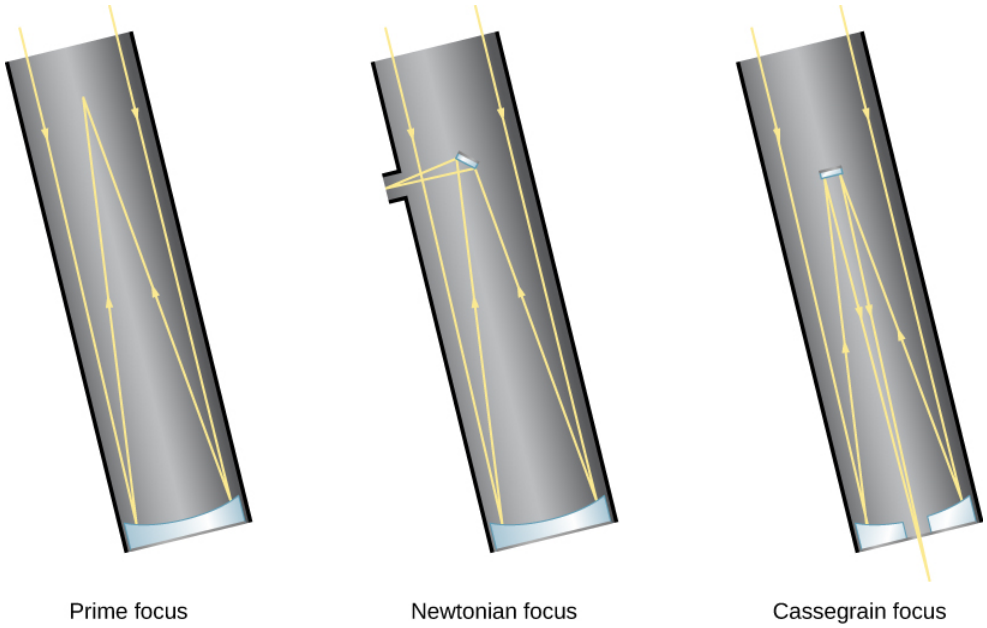


Figure 6.6 : Focus Arrangements for Reflecting Telescopes. Reflecting telescopes have different options for where the light is brought to a focus. With prime focus, light is detected where it comes to a focus after reflecting from the primary mirror. With Newtonian focus, light is reflected by a small secondary mirror off to one side, where it can be detected (see also Figure 6.5). Most large professional telescopes have a Cassegrain focus in which light is reflected by the secondary mirror down through a hole in the primary mirror to an observing station below the telescope.

Making Connections: Choosing Your Own Telescope

If the astronomy course you are taking whets your appetite for exploring the sky further, you may be thinking about buying your own telescope. Many excellent amateur telescopes are available, and some research is required to find the best model for your needs. Some good sources of information about personal telescopes are the two popular US magazines aimed at amateur astronomers: *Sky & Telescope* and *Astronomy*. Both carry regular articles with advice, reviews, and advertisements from reputable telescope dealers.

Some of the factors that determine which telescope is right for you depend upon your preferences:

- Will you be setting up the telescope in one place and leaving it there, or do you want an instrument that is portable and can come with you on outdoor excursions? How portable should it be, in terms of size and weight?
- Do you want to observe the sky with your eyes only, or do you want to take photographs? (Long-exposure photography, for example, requires a good clock drive to turn your telescope to compensate for Earth's rotation.)
- What types of objects will you be observing? Are you interested primarily in comets, planets, star clusters, or galaxies, or do you want to observe all kinds of celestial sights?

You may not know the answers to some of these questions yet. For this reason, you may want to "test-drive" some telescopes first. Most communities have amateur astronomy clubs that sponsor star parties open to the public. The members of those clubs often know a lot about telescopes and can share their ideas with you. Your instructor may know where the nearest amateur astronomy club meets; or, to find a club near you, use the websites suggested in Appendix B.

Furthermore, you may already have an instrument like a telescope at home (or have access to one through a relative or friend). Many amateur astronomers recommend starting your survey of the sky with a good pair of binoculars. These are easily carried around and can show you many objects not visible (or clear) to the unaided eye.

When you are ready to purchase a telescope, you might find the following ideas useful:

- The key characteristic of a telescope is the aperture of the main mirror or lens; when someone says they have a 6-inch or 8-inch telescope, they mean the diameter of the collecting surface. The larger the aperture, the more light you can gather, and the fainter the objects you can see or photograph.
- Telescopes of a given aperture that use lenses (refractors) are typically more expensive than those using mirrors (reflectors) because both sides of a lens must be polished to great accuracy. And, because the light passes through it, the lens must be made of high-quality glass throughout. In contrast, only the front surface of a mirror must be accurately polished.
- Magnification is not one of the criteria on which to base your choice of a telescope. As we discussed, the magnification of the image is done by a smaller eyepiece, so the magnification can be adjusted by changing eyepieces. However, a telescope will magnify not only the astronomical object you are viewing but also the turbulence of Earth's atmosphere. If the magnification is too high, your image will shimmer and shake and be difficult to view. A good telescope will come with a variety of eyepieces that stay within the range of useful magnification.
- The mount of a telescope (the structure on which it rests) is one of its most critical elements. Because a telescope shows a tiny field of view, which is magnified significantly, even the smallest vibration or jarring of the telescope can move the object you are viewing around or out of your field of view. A sturdy and stable mount is essential for serious viewing or photography (although it clearly affects how portable your telescope can be).
- A telescope requires some practice to set up and use effectively. Don't expect everything to go perfectly on your first try. Take some time to read the instructions. If a local amateur astronomy club is nearby, use it as a resource.

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6.3: Telescopes Today

Learning Objectives

By the end of this section, you will be able to:

- Recognize the largest visible-light and infrared telescopes in operation today
- Discuss the factors relevant to choosing an appropriate telescope site
- Define the technique of adaptive optics and describe the effects of the atmosphere on astronomical observations

Since Newton's time, when the sizes of the mirrors in telescopes were measured in inches, reflecting telescopes have grown ever larger. In 1948, US astronomers built a telescope with a 5-meter (200-inch) diameter mirror on Palomar Mountain in Southern California. It remained the largest visible-light telescope in the world for several decades. The giants of today, however, have primary mirrors (the largest mirrors in the telescope) that are 8- to 10-meters in diameter, and larger ones are being built (Figure 6.7).

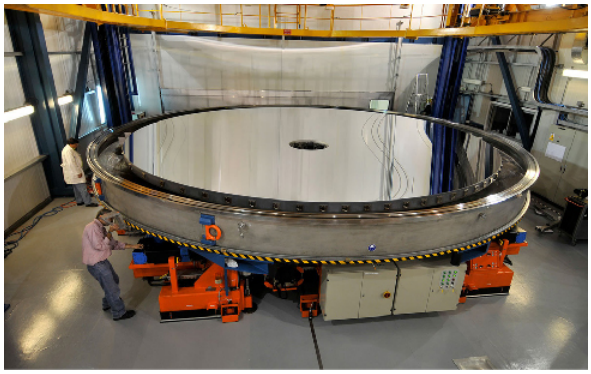


Figure 6.7 : Large Telescope Mirror. This image shows one of the primary mirrors of the European Southern Observatory's Very Large Telescope, named Yepun, just after it was recoated with aluminum. The mirror is a little over 8 meters in diameter. (credit: ESO/G. Huedepohl)

Modern Visible-Light and Infrared Telescopes

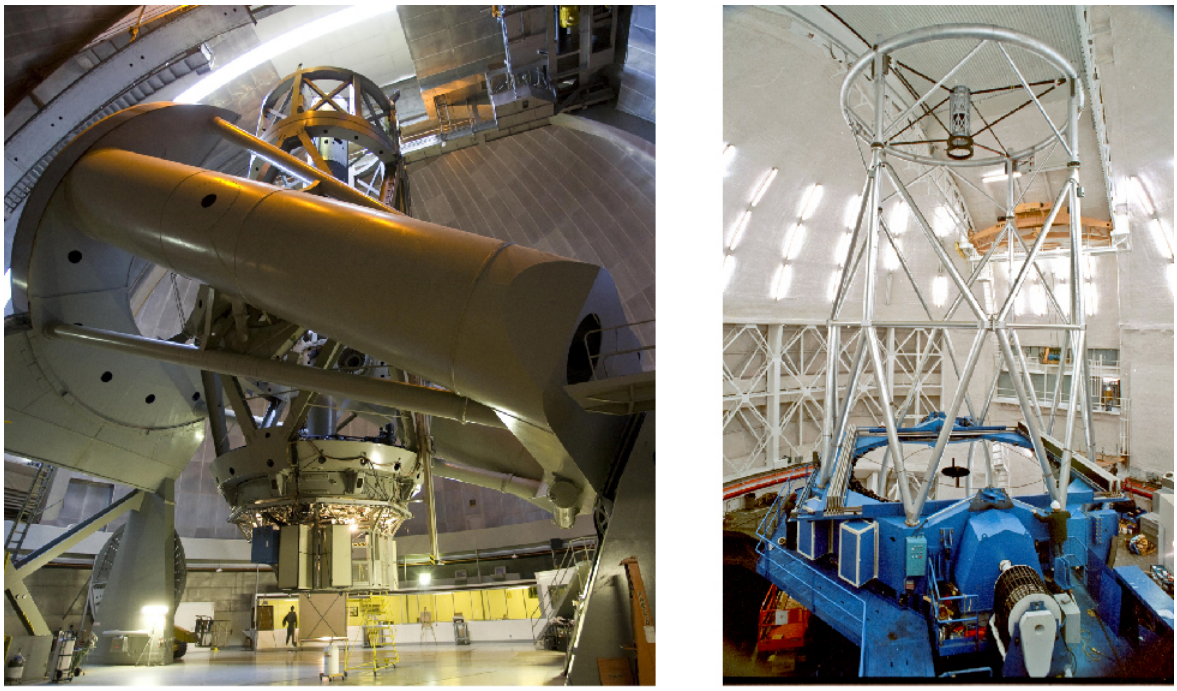
The decades starting in 1990 saw telescope building around the globe grow at an unprecedented rate. (See Table 6.1, which also includes websites for each telescope in case you want to visit or learn more about them.) Technological advancements had finally made it possible to build telescopes significantly larger than the 5-meter telescope at Palomar at a reasonable cost. New technologies have also been designed to work well in the infrared, and not just visible, wavelengths.

Table 6.1: Large Single-Dish Visible-Light and Infrared Telescopes

Aperture (m)	Telescope Name	Location	Status	Website
39	European Extremely Large Telescope (E-ELT)	Cerro Armazonas, Chile	First light 2025 (estimated)	www.eso.org/sci/facilities/eelt
30	Thirty-Meter Telescope (TMT)	Maunakea, HI	First light 2025 (estimated)	www.tmt.org
24.5	Giant Magellan Telescope (GMT)	Las Campanas Observatory, Chile	First light 2025 (estimated)	www.gmto.org
11.1×9.9	Southern African Large Telescope (SALT)	Sutherland, South Africa	2005	www.salt.ac.za
10.4	Gran Telescopio Canarias (GTC)	La Palma, Canary Islands	First light 2007	http://www.gtc.iac.es

Aperture (m)	Telescope Name	Location	Status	Website
10.0	Keck I and II (two telescopes)	Maunakea, HI	Completed 1993–96	www.keckobservatory.org
9.1	Hobby–Eberly Telescope (HET)	Mount Locke, TX	Completed 1997	www.as.utexas.edu/mcdonald/het
8.4	Large Binocular Telescope (LBT) (two telescopes)	Mount Graham, AZ	First light 2004	www.lbto.org
8.4	Large Synoptic Survey Telescope (Rubin Obs.)	The Cerro Pachón, Chile	First light 2021	www.lsst.org
8.3	Subaru Telescope	Maunakea, HI	First light 1998	www.naoj.org
8.2	Very Large Telescope (VLT)	Cerro Paranal, Chile	All four telescopes completed 2000	www.eso.org/public/teles-instr/paranal
8.1	Gemini North and Gemini South	Maunakea, HI (North) and Cerro Pachón, Chile (South)	First light 1999 (North), First light 2000 (South)	www.gemini.edu
6.5	Magellan Telescopes (two telescopes: Baade and Landon Clay)	Las Campanas, Chile	First light 2000 and 2002	obs.carnegiescience.edu/Magellan
6.5	Multi-Mirror Telescope (MMT)	Mount Hopkins, AZ	Completed 1979	www.mmto.org
6.0	Big Telescope Altazimuth (BTA-6)	Mount Pastukhov, Russia	Completed 1976	w0.sao.ru/Doc-en/Telescopes/bta/descrip.html
5.1	Hale Telescope	Mount Palomar, CA	Completed 1948	www.astro.caltech.edu/palomar/about/telescopes/hale.html

The differences between the Palomar telescope and the modern Gemini North telescope (to take an example) are easily seen in Figure 6.8. The Palomar telescope is a massive steel structure designed to hold the 14.5-ton primary mirror with a 5-meter diameter. Glass tends to sag under its own weight; hence, a huge steel structure is needed to hold the mirror. A mirror 8 meters in diameter, the size of the Gemini North telescope, if it were built using the same technology as the Palomar telescope, would have to weigh at least eight times as much and would require an enormous steel structure to support it.



(a) (b)

Figure 6.8 : Modern Reflecting Telescopes. (a) The Palomar 5-meter reflector: The Hale telescope on Palomar Mountain has a complex mounting structure that enables the telescope (in the open “tube” pointing upward in this photo) to swing easily into any position. (b) The Gemini North 8-meter telescope: The Gemini North mirror has a larger area than the Palomar mirror, but note how much less massive the whole instrument seems. (credit a: modification of work by Caltech/Palomar Observatory; credit b: modification of work by Gemini Observatory/AURA)

The 8-meter Gemini North telescope looks like a featherweight by contrast, and indeed it is. The mirror is only about 8 inches thick and weighs 24.5 tons, less than twice as much as the Palomar mirror. The Gemini North telescope was completed about 50 years after the Palomar telescope. Engineers took advantage of new technologies to build a telescope that is much lighter in weight relative to the size of the primary mirror. The Gemini mirror does sag, but with modern computers, it is possible to measure that sag many times each second and apply forces at 120 different locations to the back of the mirror to correct the sag, a process called *active control*. Seventeen telescopes with mirrors 6.5 meters in diameter and larger have been constructed since 1990.

The twin 10-meter Keck telescopes on Maunakea, which were the first of these new-technology instruments, use precision control in an entirely novel way. Instead of a single primary mirror 10 meters in diameter, each Keck telescope achieves its larger aperture by combining the light from 36 separate hexagonal mirrors, each 1.8 meters wide (Figure 6.9). Computer-controlled actuators

(motors) constantly adjust these 36 mirrors so that the overall reflecting surface acts like a single mirror with just the right shape to collect and focus the light into a sharp image.

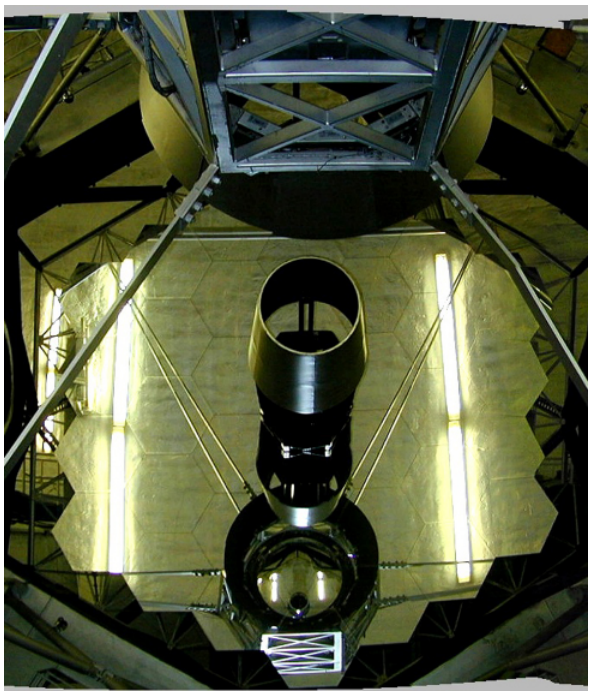


Figure 6.9 : Thirty-Six Eyes Are Better Than One. The mirror of the 10-meter Keck telescope is composed of 36 hexagonal sections. (credit: NASA)

Link to Learning

Learn more about the Keck Observatory on Maunakea through this History Channel clip on the telescopes and the work that they do.

In addition to holding the mirror, the steel structure of a telescope is designed so that the entire telescope can be pointed quickly toward any object in the sky. Since Earth is rotating, the telescope must have a motorized drive system that moves it very smoothly from east to west at exactly the same rate that Earth is rotating from west to east, so it can continue to point at the object being observed. All this machinery must be housed in a dome to protect the telescope from the elements. The dome has an opening in it that can be positioned in front of the telescope and moved along with it, so that the light from the objects being observed is not blocked.

Voyagers in Astronomy: George Ellery Hale: Master Telescope Builder

George Ellery Hale (Figure 6.10) was a giant among early telescope builders. Not once, but four times, he initiated projects that led to the construction of what was the world's largest telescope at the time. And he was a master at winning over wealthy benefactors to underwrite the construction of these new instruments.



Figure 6.10 : George Ellery Hale (1868–1938). Hale's work led to the construction of several major telescopes, including the 40-inch refracting telescope at Yerkes Observatory, and three reflecting telescopes: the 60-inch Hale and 100-inch Hooker telescopes at Mount Wilson Observatory, and the 200-inch Hale Telescope at Palomar Observatory.

Hale's training and early research were in solar physics. In 1892, at age 24, he was named associate professor of astral physics and director of the astronomical observatory at the University of Chicago. At the time, the largest telescope in the world was the 36-inch refractor at the Lick Observatory near San Jose, California. Taking advantage of an existing glass blank for a 40-inch telescope, Hale set out to raise money for a larger telescope than the one at Lick. One prospective donor was Charles T. Yerkes, who, among other things, ran the trolley system in Chicago.

Hale wrote to Yerkes, encouraging him to support the construction of the giant telescope by saying that "the donor could have no more enduring monument. It is certain that Mr. Lick's name would not have been nearly so widely known today were it not for the famous observatory established as a result of his munificence." Yerkes agreed, and the new telescope was completed in May 1897; it remains the largest refractor in the world (Figure 6.11).



Figure 6.11 : World’s Largest Refractor. The Yerkes 40-inch (1-meter) telescope.

Even before the completion of the Yerkes refractor, Hale was not only dreaming of building a still larger telescope but was also taking concrete steps to achieve that goal. In the 1890s, there was a major controversy about the relative quality of refracting and reflecting telescopes. Hale realized that 40 inches was close to the maximum feasible aperture for refracting telescopes. If telescopes with significantly larger apertures were to be built, they would have to be reflecting telescopes.

Using funds borrowed from his own family, Hale set out to construct a 60-inch reflector. For a site, he left the Midwest for the much better conditions on Mount Wilson—at the time, a wilderness peak above the small city of Los Angeles. In 1904, at the age of 36, Hale received funds from the Carnegie Foundation to establish the Mount Wilson Observatory. The 60-inch mirror was placed in its mount in December 1908.

Two years earlier, in 1906, Hale had already approached John D. Hooker, who had made his fortune in hardware and steel pipe, with a proposal to build a 100-inch telescope. The technological risks were substantial. The 60-inch telescope was not yet complete, and the usefulness of large reflectors for astronomy had yet to be demonstrated. George Ellery Hale’s brother called him “the greatest gambler in the world.” Once again, Hale successfully obtained funds, and the 100-inch telescope was completed in November 1917. (It was with this telescope that Edwin Hubble was able to establish that the spiral nebulae were separate islands of stars—or galaxies—quite removed from our own Milky Way.)

Hale was not through dreaming. In 1926, he wrote an article in *Harper’s Magazine* about the scientific value of a still larger telescope. This article came to the attention of the Rockefeller Foundation, which granted $6 million for the construction of a 200-inch telescope. Hale died in 1938, but the 200-inch (5-meter) telescope on Palomar Mountain was dedicated 10 years later and is now named in Hale’s honor.

Picking the Best Observing Sites

A telescope like the Gemini or Keck telescope costs about $100 million to build. That kind of investment demands that the telescope be placed in the best possible site. Since the end of the nineteenth century, astronomers have realized that the best observatory sites are on mountains, far from the lights and pollution of cities. Although a number of urban observatories remain,

especially in the large cities of Europe, they have become administrative centers or museums. The real action takes place far away, often on desert mountains or isolated peaks in the Atlantic and Pacific Oceans, where we find the staff's living quarters, computers, electronic and machine shops, and of course the telescopes themselves. A large observatory today requires a supporting staff of 20 to 100 people in addition to the astronomers.

The performance of a telescope is determined not only by the size of its mirror but also by its location. Earth's atmosphere, so vital to life, presents challenges for the observational astronomer. In at least four ways, our air imposes limitations on the usefulness of telescopes:

1. The most obvious limitation is weather conditions such as clouds, wind, and rain. At the best sites, the weather is clear as much as 75% of the time.
2. Even on a clear night, the atmosphere filters out a certain amount of starlight, especially in the infrared, where the absorption is due primarily to water vapor. Astronomers therefore prefer dry sites, generally found at high altitudes.
3. The sky above the telescope should be dark. Near cities, the air scatters the glare from lights, producing an illumination that hides the faintest stars and limits the distances that can be probed by telescopes. (Astronomers call this effect light pollution.) Observatories are best located at least 100 miles from the nearest large city.
4. Finally, the air is often unsteady; light passing through this turbulent air is disturbed, resulting in blurred star images. Astronomers call these effects "bad seeing." When seeing is bad, images of celestial objects are distorted by the constant twisting and bending of light rays by turbulent air.

The best observatory sites are therefore high, dark, and dry. The world's largest telescopes are found in such remote mountain locations as the Andes Mountains of Chile (Figure 6.12), the desert peaks of Arizona, the Canary Islands in the Atlantic Ocean, and Maunakea in Hawaii, a dormant volcano with an altitude of 13,700 feet (4200 meters).

Link to Learning

Light pollution is a problem not just for professional astronomers but for everyone who wants to enjoy the beauty of the night sky. In addition research is now showing that it can disrupt the life cycle of animals with whom we share the urban and suburban landscape. And the light wasted shining into the sky leads to unnecessary municipal expenses and use of fossil fuels. Concerned people have formed an organization, the International Dark-Sky Association, whose website is full of good information. A citizen science project called *Globe at Night* allows you to measure the light levels in your community by counting stars and to compare it to others around the world. Recently, a new threat to dark skies has emerged. A number of commercial companies are planning and launching large swarms of satellites into low-Earth orbit to provide internet access around the world. Unfortunately, these satellites reflect sunlight and have already begun to ruin astronomical photographs the world over. See the Further Exploration section at the end of this chapter for more resources on this topic. If you get interested in this topic and want to do a paper for your astronomy course or another course while you are in college, the *Dark Night Skies guide* can point you to a variety of resources on the topic.



Figure 6.12 : High and Dry Site. Cerro Paranal, a mountain summit 2.7 kilometers above sea level in Chile's Atacama Desert, is the site of the European Southern Observatory's Very Large Telescope. This photograph shows the four 8-meter telescope buildings on the site and vividly illustrates that astronomers prefer high, dry sites for their instruments. The 4.1-meter Visible and Infrared Survey Telescope for Astronomy (VISTA) can be seen in the distance on the next mountain peak. (credit: ESO)

The Resolution of a Telescope

In addition to gathering as much light as they can, astronomers also want to have the sharpest images possible. Resolution refers to the precision of detail present in an image: that is, the smallest features that can be distinguished. Astronomers are always eager to make out more detail in the images they study, whether they are following the weather on Jupiter or trying to peer into the violent heart of a “cannibal galaxy” that recently ate its neighbor for lunch.

One factor that determines how good the resolution will be is the size of the telescope. Larger apertures produce sharper images. Until very recently, however, visible-light and infrared telescopes on Earth’s surface could not produce images as sharp as the theory of light said they should.

The problem—as we saw earlier in this chapter—is our planet’s atmosphere, which is turbulent. It contains many small-scale blobs or cells of gas that range in size from inches to several feet. Each cell has a slightly different temperature from its neighbor, and each cell acts like a lens, bending (refracting) the path of the light by a small amount. This bending slightly changes the position where each light ray finally reaches the detector in a telescope. The cells of air are in motion, constantly being blown through the light path of the telescope by winds, often in different directions at different altitudes. As a result, the path followed by the light is constantly changing.

For an analogy, think about watching a parade from a window high up in a skyscraper. You decide to throw some confetti down toward the marchers. Even if you drop a handful all at the same time and in the same direction, air currents will toss the pieces around, and they will reach the ground at different places. As we described earlier, we can think of the light from the stars as a series of parallel beams, each making its way through the atmosphere. Each path will be slightly different, and each will reach the detector of the telescope at a slightly different place. The result is a blurred image, and because the cells are being blown by the wind, the nature of the blur will change many times each second. You have probably noticed this effect as the “twinkling” of stars seen from Earth. The light beams are bent enough that part of the time they reach your eye, and part of the time some of them miss, thereby making the star seem to vary in brightness. In space, however, the light of the stars is steady.

Astronomers search the world for locations where the amount of atmospheric blurring, or turbulence, is as small as possible. It turns out that the best sites are in coastal mountain ranges and on isolated volcanic peaks in the middle of an ocean. Air that has flowed long distances over water before it encounters land is especially stable.

The resolution of an image is measured in units of angle on the sky, typically in units of arcseconds. One arcsecond is 1/3600 degree, and there are 360 degrees in a full circle. So we are talking about tiny angles on the sky. To give you a sense of just how tiny, we might note that 1 arcsecond is how big a quarter would look when seen from a distance of 5 kilometers. The best images obtained from the ground with traditional techniques reveal details as small as several tenths of an arcsecond across. This image size is remarkably good. One of the main reasons for launching the Hubble Space Telescope was to escape Earth’s atmosphere and obtain even sharper images.

But since we can’t put every telescope into space, astronomers have devised a technique called adaptive optics that can beat Earth’s atmosphere at its own game of blurring. This technique (which is most effective in the infrared region of the spectrum with our current technology) makes use of a small flexible mirror placed in the beam of a telescope. A sensor measures how much the atmosphere has distorted the image, and as often as 500 times per second, it sends instructions to the flexible mirror on how to change shape in order to compensate for distortions produced by the atmosphere. The light is thus brought back to an almost perfectly sharp focus at the detector. Figure 6.13 shows just how effective this technique is. With adaptive optics, ground-based telescopes can achieve resolutions of 0.1 arcsecond or a little better in the infrared region of the spectrum. This impressive figure is the equivalent of the resolution that the Hubble Space Telescope achieves in the visible-light region of the spectrum.

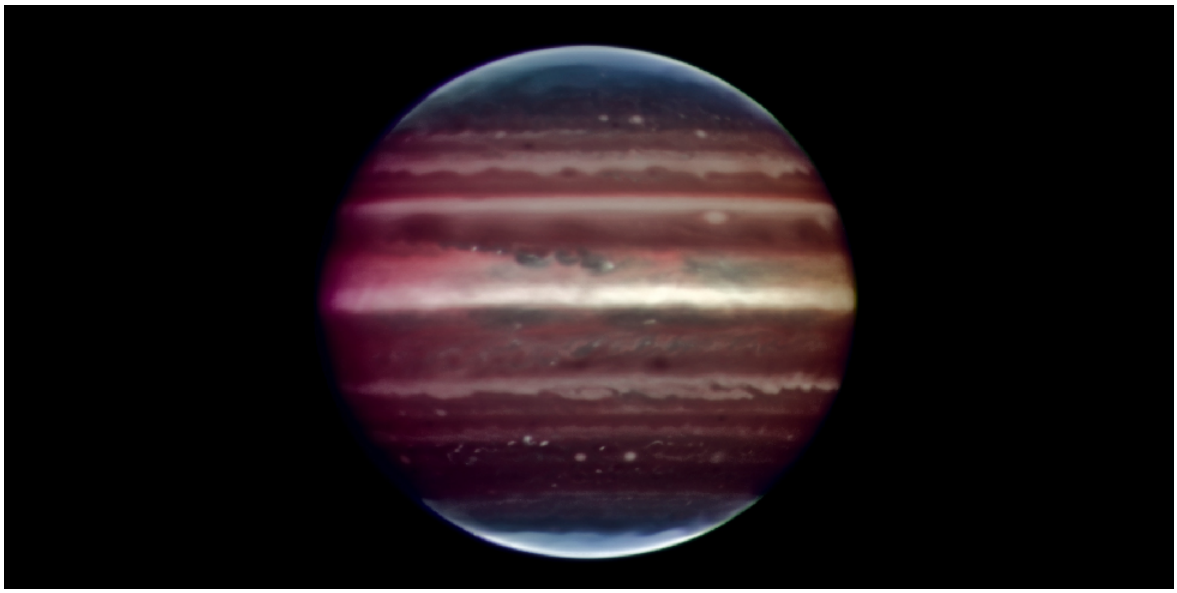


Figure 6.13 : Power of Adaptive Optics. One of the clearest pictures of Jupiter ever taken from the ground, this image was produced with adaptive optics using an 8-meter-diameter telescope at the Very Large Telescope in Chile. Adaptive optics uses infrared wavelengths to remove atmospheric blurring, resulting in a much clearer image. (credit: modification of work by ESO, F.Marchis, M.Wong (UC Berkeley); E.Marchetti, P.Amico, S.Tordo (ESO))

Astronomy Basics: How Astronomers Really Use Telescopes

In the popular view (and some bad movies), an astronomer spends most nights in a cold observatory peering through a telescope, but this is not very accurate today. Most astronomers do not live at observatories, but near the universities or laboratories where they work. An astronomer might spend only a week or so each year observing at the telescope and the rest of the time measuring or analyzing the data acquired from large project collaborations and dedicated surveys. Many astronomers use radio telescopes for space experiments, which work just as well during the daylight hours. Still others work at purely theoretical problems using supercomputers and never observe at a telescope of any kind.

Even when astronomers are observing with large telescopes, they seldom peer through them. Electronic detectors permanently record the data for detailed analysis later. At some observatories, observations may be made remotely, with the astronomer sitting at a computer thousands of miles away from the telescope.

Time on major telescopes is at a premium, and an observatory director will typically receive many more requests for telescope time than can be accommodated during the year. Astronomers must therefore write a convincing proposal explaining how they would like to use the telescope and why their observations will be important to the progress of astronomy. A committee of astronomers is then asked to judge and rank the proposals, and time is assigned only to those with the greatest merit. Even if your proposal is among the high-rated ones, you may have to wait many months for your turn. If the skies are cloudy on the nights you have been assigned, it may be more than a year before you get another chance.

Some older astronomers still remember long, cold nights spent alone in an observatory dome, with only music from a tape recorder or an all-night radio station for company. The sight of the stars shining brilliantly hour after hour through the open slit

in the observatory dome was unforgettable. So, too, was the relief as the first pale light of dawn announced the end of a 12-hour observation session. Astronomy is much easier today, with teams of observers working together, often at their computers, in a warm room. Those who are more nostalgic, however, might argue that some of the romance has gone from the field, too.

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6.4: Visible-Light Detectors and Instruments

Learning Objectives

By the end of this section, you will be able to:

- Describe the difference between photographic plates and charge-coupled devices
- Describe the unique difficulties associated with infrared observations and their solutions
- Describe how a spectrometer works

After a telescope collects radiation from an astronomical source, the radiation must be *detected* and measured. The first detector used for astronomical observations was the human eye, but it suffers from being connected to an imperfect recording and retrieving device—the human brain. Photography and modern electronic detectors have eliminated the quirks of human memory by making a permanent record of the information from the cosmos.

The eye also suffers from having a very short *integration time*; it takes only a fraction of a second to add light energy together before sending the image to the brain. One important advantage of modern detectors is that the light from astronomical objects can be collected by the detector over longer periods of time; this technique is called “taking a long exposure.” Exposures of several hours are required to detect very faint objects in the cosmos.

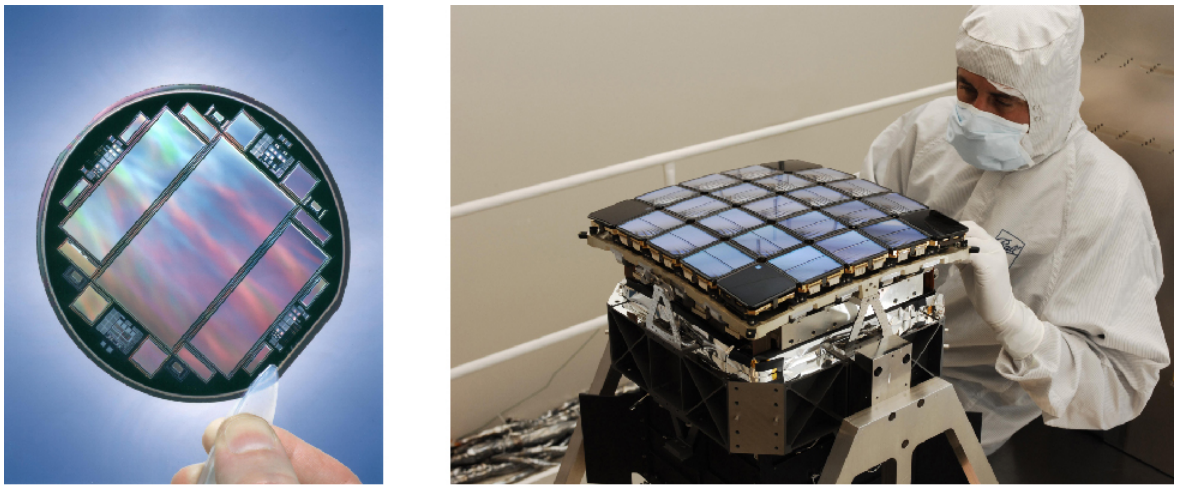
Before the light reaches the detector, astronomers today normally use some type of instrument to sort the light according to wavelength. The instrument may be as simple as colored filters, which transmit light within a specified range of wavelengths. A red transparent plastic is an everyday example of a filter that transmits only the red light and blocks the other colors. After the light passes through a filter, it forms an image that astronomers can then use to measure the apparent brightness and color of objects. We will show you many examples of such images in the later chapters of this book, and we will describe what we can learn from them.

Alternatively, the instrument between telescope and detector may be one of several devices that spread the light out into its full rainbow of colors so that astronomers can measure individual lines in the spectrum. Such an instrument (which you learned about in the chapter on Radiation and Spectra) is called a *spectrometer* because it allows astronomers to measure (to meter) the spectrum of a source of radiation. Whether a filter or a spectrometer, both types of wavelength-sorting instruments still have to use detectors to record and measure the properties of light.

Photographic and Electronic Detectors

Throughout most of the twentieth century, photographic film or *glass plates* served as the prime astronomical detectors, whether for photographing spectra or direct images of celestial objects. In a photographic plate, a light-sensitive chemical coating is applied to a piece of glass that, when developed, provides a lasting record of the image. At observatories around the world, vast collections of photographs preserve what the sky has looked like during the past 100 years. Photography represents a huge improvement over the human eye, but it still has limitations. Photographic films are inefficient: only about 1% of the light that actually falls on the film contributes to the chemical change that makes the image; the rest is wasted.

Astronomers today have much more efficient electronic detectors to record astronomical images. Most often, these are charge-coupled devices (CCDs), which are similar to the detectors used in video camcorders or in digital cameras (like the one more and more students have on their cell phones) (see Figure 6.14). In a CCD, photons of radiation hitting any part of the detector generate a stream of charged particles (electrons) that are stored and counted at the end of the exposure. Each place where the radiation is counted is called a pixel (picture element), and modern detectors can count the photons in millions of pixels (megapixels, or MPs).



(a) (b)

Figure 6.14 : Charge-Coupled Devices (CCDs). (a) This CCD is a mere 300-micrometers thick (thinner than a human hair) yet holds more than 21 million pixels. (b) This matrix of 42 CCDs served the Kepler telescope. (credit a: modification of work by US Department of Energy; credit b: modification of work by NASA and Ball Aerospace)

Because CCDs typically record as much as 60–70% of all the photons that strike them, and the best silicon and infrared CCDs exceed 90% sensitivity, we can detect much fainter objects. Among these are many small moons around the outer planets, icy dwarf planets beyond Pluto, and dwarf galaxies of stars. CCDs also provide more accurate measurements of the brightness of astronomical objects than photography, and their output is digital—in the form of numbers that can go directly into a computer for analysis.

Infrared Observations

Observing the universe in the infrared band of the spectrum presents some additional challenges. The infrared region extends from wavelengths near 1 micrometer (μm), which is about the long wavelength sensitivity limit of both CCDs and photography, to 100 micrometers or longer. Recall from the discussion on radiation and spectra that infrared is “heat radiation” (given off at temperatures that we humans are comfortable with). The main challenge to astronomers using infrared is to distinguish between the tiny amount of heat radiation that reaches Earth from stars and galaxies, and the much greater heat radiated by the telescope itself and our planet’s atmosphere.

Typical temperatures on Earth’s surface are near 300 K, and the atmosphere through which observations are made is only a little cooler. According to Wien’s law (from the chapter on Radiation and Spectra), the telescope, the observatory, and even the sky are radiating infrared energy with a peak wavelength of about 10 micrometers. To infrared eyes, everything on Earth is brightly aglow —including the telescope and camera (Figure 6.15). The challenge is to detect faint cosmic sources against this sea of infrared light. Another way to look at this is that an astronomer using infrared must always contend with the situation that a visible-light observer would face if working in broad daylight with a telescope and optics lined with bright fluorescent lights.



Figure 6.15 : Infrared Eyes. Infrared waves can penetrate places in the universe from which light is blocked, as shown in this infrared image where the plastic bag blocks visible light but not infrared. (credit: NASA/JPL-Caltech/R. Hurt (SSC))

To solve this problem, astronomers must protect the infrared detector from nearby radiation, just as you would shield photographic film from bright daylight. Since anything warm radiates infrared energy, the detector must be isolated in very cold surroundings; often, it is held near absolute zero (1 to 3 K) by immersing it in liquid helium. The second step is to reduce the radiation emitted by the telescope structure and optics, and to block this heat from reaching the infrared detector.

Link to Learning

Check out The Infrared Zoo to get a sense of what familiar objects look like with infrared radiation. Slide the slider to change the wavelength of radiation for the picture, and click the arrow to see other animals.

Spectroscopy

Spectroscopy is one of the astronomer's most powerful tools, providing information about the composition, temperature, motion, and other characteristics of celestial objects. More than half of the time spent on most large telescopes is used for spectroscopy.

The many different wavelengths present in light can be separated by passing them through a spectrometer to form a spectrum. The design of a simple spectrometer is illustrated in Figure 6.16. Light from the source (actually, the image of a source produced by the telescope) enters the instrument through a small hole or narrow slit, and is collimated (made into a beam of parallel rays) by a lens. The light then passes through a prism, producing a spectrum: different wavelengths leave the prism in different directions because each wavelength is bent by a different amount when it enters and leaves the prism. A second lens placed behind the prism focuses the many different images of the slit or entrance hole onto a CCD or other detecting device. This collection of images (spread out by color) is the spectrum that astronomers can then analyze at a later point. As spectroscopy spreads the light out into more and more collecting bins, fewer photons go into each bin, so either a larger telescope is needed or the integration time must be greatly increased—usually both.

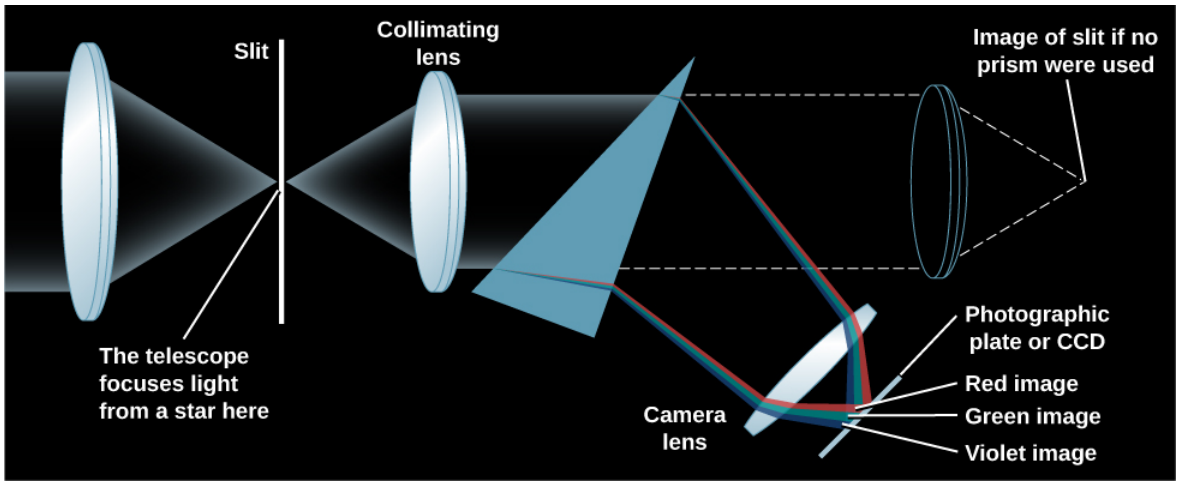


Figure 6.16 : Prism Spectrometer. The light from the telescope is focused on a slit. A prism (or grating) disperses the light into a spectrum, which is then photographed or recorded electronically.

In practice, astronomers today are more likely to use a different device, called a *grating*, to disperse the spectrum. A grating is a piece of material with thousands of grooves on its surface. While it functions completely differently, a grating, like a prism, also spreads light out into a spectrum.

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6.5: Radio Telescopes

Learning Objectives

By the end of this section, you will be able to:

- Describe how radio waves from space are detected
- Identify the world's largest radio telescopes
- Define the technique of interferometry and discuss the benefits of interferometers over single-dish telescopes

In addition to visible and infrared radiation, radio waves from astronomical objects can also be detected from the surface of Earth. In the early 1930s, Karl G. Jansky, an engineer at Bell Telephone Laboratories, was experimenting with antennas for long-range radio communication when he encountered some mysterious static—radio radiation coming from an unknown source (Figure 6.17). He discovered that this radiation came in strongest about four minutes earlier on each successive day and correctly concluded that since Earth's sidereal rotation period (how long it takes us to rotate relative to the stars) is four minutes shorter than a solar day, the radiation must be originating from some region fixed on the celestial sphere. Subsequent investigation showed that the source of this radiation was part of the Milky Way Galaxy; Jansky had discovered the first source of cosmic radio waves.

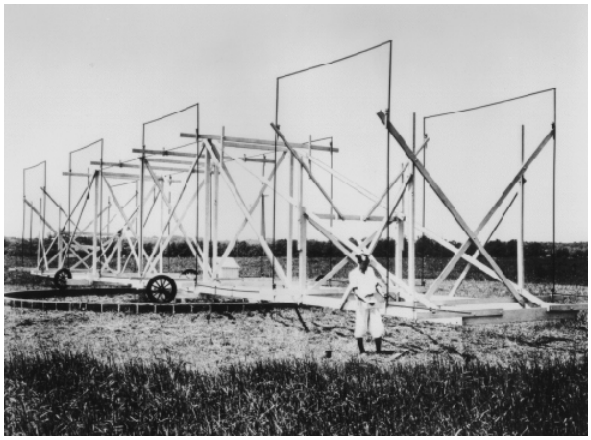


Figure 6.17 : First Radio Telescope. This rotating radio antenna was used by Jansky in his serendipitous discovery of radio radiation from the Milky Way.

In 1936, Grote Reber, who was an amateur astronomer interested in radio communications, used galvanized iron and wood to build the first antenna specifically designed to receive cosmic radio waves. Over the years, Reber built several such antennas and used them to carry out pioneering surveys of the sky for celestial radio sources; he remained active in radio astronomy for more than 30 years. During the first decade, he worked practically alone because professional astronomers had not yet recognized the vast potential of radio astronomy.

Detection of Radio Energy from Space

It is important to understand that radio waves cannot be "heard": they are not the sound waves you hear coming out of the radio receiver in your home or car. Like light, radio waves are a form of electromagnetic radiation, but unlike light, we cannot detect them with our senses—we must rely on electronic equipment to pick them up. In commercial radio broadcasting, we encode sound information (music or a newscaster's voice) into radio waves. These must be decoded at the other end and then turned back into sound by speakers or headphones.

The radio waves we receive from space do not, of course, have music or other program information encoded in them. If cosmic radio signals were translated into sound, they would sound like the static you hear when scanning between stations. Nevertheless, there is information in the radio waves we receive—information that can tell us about the chemistry and physical conditions of the sources of the waves.

Just as vibrating charged particles can produce electromagnetic waves (see the Radiation and Spectra chapter), electromagnetic waves can make charged particles move back and forth. Radio waves can produce a current in conductors of electricity such as metals. An antenna is such a conductor: it intercepts radio waves, which create a feeble current in it. The current is then amplified in a radio receiver until it is strong enough to measure or record. Like your television or radio, receivers can be tuned to select a

single frequency (channel). In astronomy, however, it is more common to use sophisticated data-processing techniques that allow thousands of separate frequency bands to be detected simultaneously. Thus, the astronomical radio receiver operates much like a spectrometer on a visible-light or infrared telescope, providing information about how much radiation we receive at each wavelength or frequency. After computer processing, the radio signals are recorded on magnetic disks for further analysis.

Radio waves are reflected by conducting surfaces, just as light is reflected from a shiny metallic surface, and according to the same laws of optics. A radio-reflecting telescope consists of a concave metal reflector (called a *dish*), analogous to a telescope mirror. The radio waves collected by the dish are reflected to a focus, where they can then be directed to a receiver and analyzed. Because humans are such visual creatures, radio astronomers often construct a pictorial representation of the radio sources they observe. Figure 6.18 shows such a radio image of a distant galaxy, where radio telescopes reveal vast jets and complicated regions of radio emissions that are completely invisible in photographs taken with light.

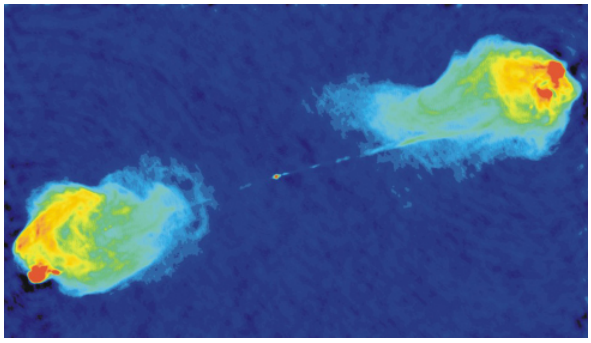


Figure 6.18 : Radio Image. This image has been constructed of radio observations at the Very Large Array of a galaxy called Cygnus A. Colors have been added to help the eye sort out regions of different radio intensities. Red regions are the most intense, blue the least. The visible galaxy would be a small dot in the center of the image. The radio image reveals jets of expelled material (more than 160,000 light-years long) on either side of the galaxy. (credit: NRAO/AUI)

Radio astronomy is a young field compared with visible-light astronomy, but it has experienced tremendous growth in recent decades. The world's largest radio reflectors that can be pointed to any direction in the sky have apertures of 100 meters. One of these has been built at the US National Radio Astronomy Observatory in West Virginia (Figure 6.19). Table 6.2 lists some of the major radio telescopes of the world.



Figure 6.19 : Robert C. Byrd Green Bank Telescope. This fully steerable radio telescope in West Virginia went into operation in August 2000. Its dish is about 100 meters across. (credit: modification of work by "b3nscott"/Flickr)

Table 6.2: Major Radio Observatories of the World

Observatory	Location	Description	Website
Individual Radio Dishes			

Observatory	Location	Description	Website
Five-hundred-meter Aperture Spherical radio Telescope (FAST)	Guizhou, China	500-m fixed dish	fast.bao.ac.cn/en/
Arecibo Observatory	Arecibo, Puerto Rico	305-m fixed dish	www.naic.edu
Green Bank Telescope (GBT)	Green Bank, WV	110 × 100-m steerable dish	www.science.nrao.edu/facilities/gbt
Effelsberg 100-m Telescope	Bonn, Germany	100-m steerable dish	www.mpifr-bonn.mpg.de/en/effelsberg
Lovell Telescope	Manchester, England	76-m steerable dish	www.jb.man.ac.uk/aboutus/lovell
Canberra Deep Space Communication Complex (CDSCC)	Tidbinbilla, Australia	70-m steerable dish	www.cdscc.nasa.gov
Goldstone Deep Space Communications Complex (GDSCC)	Barstow, CA	70-m steerable dish	www.gdscc.nasa.gov
Parkes Observatory	Parkes, Australia	64-m steerable dish	www.parkes.atnf.csiro.au
Arrays of Radio Dishes			
Square Kilometre Array (SKA)	South Africa and Western Australia	Thousands of dishes, km^2 collecting area, partial array in 2020	www.skatelescope.org
Atacama Large Millimeter/submillimeter Array (ALMA)	Atacama desert, Northern Chile	66 7-m and 12-m dishes	www.almaobservatory.org
Jansky Very Large Array (VLA)	Socorro, New Mexico	27-element array of 25-m dishes (36-km baseline)	www.science.nrao.edu/facilities/vla
Westerbork Synthesis Radio Telescope (WSRT)	Westerbork, the Netherlands	12-element array of 25-m dishes (1.6-km baseline)	www.astron.nl/radio-observatory/public/public-0
Very Long Baseline Array (VLBA)	Ten US sites, HI to the Virgin Islands	10-element array of 25-m dishes (9000 km baseline)	www.science.nrao.edu/facilities/vlba
Australia Telescope Compact Array (ATCA)	Several sites in Australia	8-element array (seven 22-m dishes plus Parkes 64 m)	www.narrabri.atnf.csiro.au
Multi-Element Radio Linked Interferometer Network (MERLIN)	Cambridge, England, and other British sites	Network of seven dishes (the largest is 32 m)	www.e-merlin.ac.uk
Millimeter-wave Telescopes			
IRAM	Granada, Spain	30-m steerable mm-wave dish	www.iram-institute.org
James Clerk Maxwell Telescope (JCMT)	Maunakea, HI	15-m steerable mm-wave dish	www.eaobservatory.org/jcmt
Nobeyama Radio Observatory (NRO)	Minamimaki, Japan	6-element array of 10-m wave dishes	www.nro.nao.ac.jp/en

Observatory	Location	Description	Website
Hat Creek Radio Observatory (HCRO)	Cassel, CA	6-element array of 5-m wave dishes	www.sri.com/research-development/specialized-facilities/hat-creek-radio-observatory

Radio Interferometry

As we discussed earlier, a telescope's ability to show us fine detail (its resolution) depends upon its aperture, but it also depends upon the wavelength of the radiation that the telescope is gathering. The longer the waves, the harder it is to resolve fine detail in the images or maps we make. Because radio waves have such long wavelengths, they present tremendous challenges for astronomers who need good resolution. In fact, even the largest radio dishes on Earth, operating alone, cannot make out as much detail as the typical small visible-light telescope used in a college astronomy lab. To overcome this difficulty, radio astronomers have learned to sharpen their images by linking two or more radio telescopes together electronically. Two or more telescopes linked together in this way are called an interferometer.

"Interferometer" may seem like a strange term because the telescopes in an interferometer work cooperatively; they don't "interfere" with each other. Interference, however, is a technical term for the way that multiple waves interact with each other when they arrive in our instruments, and this interaction allows us to coax more detail out of our observations. The resolution of an interferometer depends upon the separation of the telescopes, not upon their individual apertures. Two telescopes separated by 1 kilometer provide the same resolution as would a single dish 1 kilometer across (although they are not, of course, able to collect as much radiation as a radio-wave bucket that is 1 kilometer across).

To get even better resolution, astronomers combine a large number of radio dishes into an interferometer array. In effect, such an array works like a large number of two-dish interferometers, all observing the same part of the sky together. Computer processing of the results permits the reconstruction of a high-resolution radio image. The most extensive such instrument in the United States is the National Radio Astronomy Observatory's Jansky Very Large Array (VLA) near Socorro, New Mexico. It consists of 27 movable radio telescopes (on railroad tracks), each having an aperture of 25 meters, spread over a total span of about 36 kilometers. By electronically combining the signals from all of its individual telescopes, this array permits the radio astronomer to make pictures of the sky at radio wavelengths comparable to those obtained with a visible-light telescope, with a resolution of about 1 arcsecond.

The Atacama Large Millimeter/submillimeter array (ALMA) in the Atacama Desert of Northern Chile (Figure 6.20), at an altitude of 16,400 feet, consists of 12 7-meter and 54 12-meter telescopes, and can achieve baselines up to 16 kilometers. Since it became operational in 2013, it has made observations at resolutions down to 6 milliarcseconds (0.006 arcseconds), a remarkable achievement for radio astronomy.

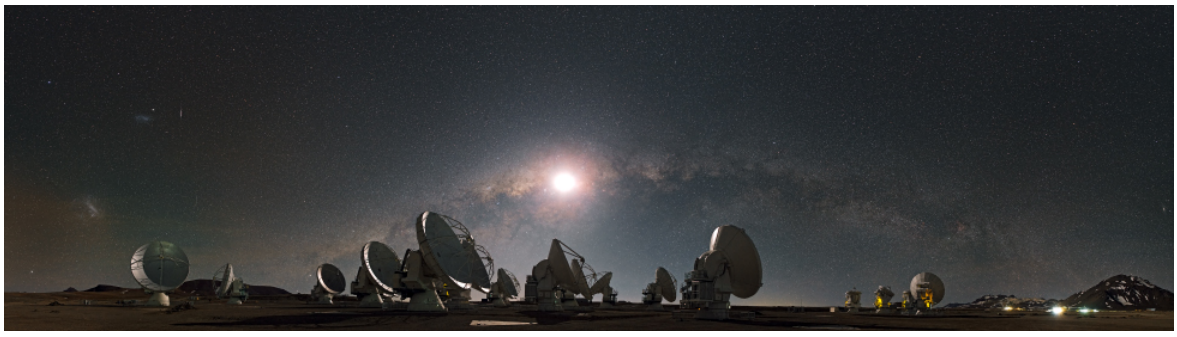


Figure 6.20 : Atacama Large Millimeter/Submillimeter Array (ALMA). Located in the Atacama Desert of Northern Chile, ALMA currently provides the highest resolution for radio observations. (credit: ESO/S. Guisard)

Link to Learning

Watch this documentary that explains the work that went into designing and building ALMA, discusses some of its first images, and explores its future.

Initially, the size of interferometer arrays was limited by the requirement that all of the dishes be physically wired together. The maximum dimensions of the array were thus only a few tens of kilometers. However, larger interferometer separations can be achieved if the telescopes do not require a physical connection. Astronomers, with the use of current technology and computing power, have learned to time the arrival of electromagnetic waves coming from space very precisely at each telescope and combine the data later. If the telescopes are as far apart as California and Australia, or as West Virginia and Crimea in Ukraine, the resulting resolution far surpasses that of visible-light telescopes.

The United States operates the Very Long Baseline Array (VLBA), made up of 10 individual telescopes stretching from the Virgin Islands to Hawaii (Figure 6.21). The VLBA, completed in 1993, can form astronomical images with a resolution of 0.0001 arcseconds, permitting features as small as 10 astronomical units (AU) to be distinguished at the center of our Galaxy.



Figure 6.21 : Very Long Baseline Array. This map shows the distribution of 10 antennas that constitute an array of radio telescopes stretching across the United States and its territories.

Recent advances in technology have also made it possible to do interferometry at visible-light and infrared wavelengths. At the beginning of the twenty-first century, three observatories with multiple telescopes each began using their dishes as interferometers, combining their light to obtain a much greater resolution. In addition, a dedicated interferometric array was built on Mt. Wilson in California. Just as in radio arrays, these observations allow astronomers to make out more detail than a single telescope could provide.

Table 6.3: Visible-Light Interferometers

Longest Baseline (m)	Telescope Name	Location	Mirrors	Status
400	CHARA Array (Center for High Angular Resolution Astronomy)	Mount Wilson, CA	Six 1-m telescopes	Operational since 2004
200	Very Large Telescope	Cerro Paranal, Chile	Four 8.2-m telescopes	Completed 2000
85	Keck I and II telescopes	Maunakea, HI	Two 10-m telescopes	Operated from 2001 to 2012
22.8	Large Binocular Telescope	Mount Graham, AZ	Two 8.4-m telescopes	First light 2004

Radar Astronomy

Radar is the technique of transmitting radio waves to an object in our solar system and then detecting the radio radiation that the object reflects back. The time required for the round trip can be measured electronically with great precision. Because we know the speed at which radio waves travel (the speed of light), we can determine the distance to the object or a particular feature on its surface (such as a mountain).

Radar observations have been used to determine the distances to planets and how fast things are moving in the solar system (using the Doppler effect, discussed in the Radiation and Spectra chapter). Radar waves have played important roles in navigating spacecraft throughout the solar system. In addition, as will be discussed in later chapters, radar observations have determined the rotation periods of Venus and Mercury, probed tiny Earth-approaching asteroids, and allowed us to investigate the mountains and valleys on the surfaces of Mercury, Venus, Mars, and the large moons of Jupiter.

Any radio dish can be used as a radar telescope if it is equipped with a powerful transmitter as well as a receiver. For many years, the most spectacular facility in the world for radar astronomy was the 1000-foot (305-meter) telescope at Arecibo in Puerto Rico (Figure 6.22). The Arecibo telescope was too large to be pointed directly at different parts of the sky. Instead, it was constructed in

a huge natural “bowl” (more than a mere dish) formed by several hills, and it was lined with reflecting metal panels. A limited ability to track astronomical sources was achieved by moving the receiver system, which was suspended on cables 100 meters above the surface of the bowl. Unfortunately, the telescope was seriously damaged in the powerful storms of 2020 and had to be decommissioned. An even larger (500-meter) radar telescope has recently gone into operation in China and is called the Five-hundred-meter Aperture Spherical Telescope (FAST).



Figure 6.22 : Largest Radio and Radar Dish. The Arecibo Observatory in Puerto Rico was the largest and most powerful astronomical radar faculty in the world and was often featured in films. In November 2020 it collapsed, damaging the 300-meter diameter “dish” and destroying the radar transmitter and receiver. (credit: National Astronomy and Ionosphere Center, Cornell U., NSF)

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6.6: Observations outside Earth's Atmosphere

Learning Objectives

By the end of this section, you will be able to:

- List the advantages of making astronomical observations from space
- Explain the importance of the Hubble Space Telescope
- Describe some of the major space-based observatories astronomers use

Earth's atmosphere blocks most radiation at wavelengths shorter than visible light, so we can only make direct ultraviolet, X-ray, and gamma ray observations from space (though indirect gamma ray observations can be made from Earth). Getting above the distorting effects of the atmosphere is also an advantage at visible and infrared wavelengths. The stars don't "twinkle" in space, so the amount of detail you can observe is limited only by the size of your instrument. On the other hand, it is expensive to place telescopes into space, and repairs can present a major challenge. This is why astronomers continue to build telescopes for use on the ground as well as for launching into space.

Airborne and Space Infrared Telescopes

Water vapor, the main source of atmospheric interference for making infrared observations, is concentrated in the lower part of Earth's atmosphere. For this reason, a gain of even a few hundred meters in elevation can make an important difference in the quality of an infrared observatory site. Given the limitations of high mountains, most of which attract clouds and violent storms, and the fact that the ability of humans to perform complex tasks degrades at high altitudes, it was natural for astronomers to investigate the possibility of observing infrared waves from airplanes and ultimately from space.

Infrared observations from airplanes have been made since the 1960s, starting with a 15-centimeter telescope on board a Learjet. From 1974 through 1995, NASA operated a 0.9-meter airborne telescope flying regularly out of the Ames Research Center south of San Francisco. Observing from an altitude of 12 kilometers, the telescope was above 99% of the atmospheric water vapor. More recently, NASA (in partnership with the German Aerospace Center) has constructed a much larger 2.5-meter telescope, called the Stratospheric Observatory for Infrared Astronomy (SOFIA), which flies in a modified Boeing 747SP (Figure 6.23).



Figure 6.23 : Stratospheric Observatory for Infrared Astronomy (SOFIA). SOFIA allows observations to be made above most of Earth's atmospheric water vapor. (credit: NASA)

Link to Learning

To find out more about SOFIA, watch this video provided by NASA's Armstrong Flight Research Center.

Getting even higher and making observations from space itself have important advantages for infrared astronomy. First is the elimination of all interference from the atmosphere. Equally important is the opportunity to cool the entire optical system of the instrument in order to nearly eliminate infrared radiation from the telescope itself. If we tried to cool a telescope within the atmosphere, it would quickly become coated with condensing water vapor and other gases, making it useless. Only in the vacuum of space can optical elements be cooled to hundreds of degrees below freezing and still remain operational.

The first orbiting infrared observatory, launched in 1983, was the Infrared Astronomical Satellite (IRAS), built as a joint project by the United States, the Netherlands, and Britain. IRAS was equipped with a 0.6-meter telescope cooled to a temperature of less than 10 K. For the first time, the infrared sky could be seen as if it were night, rather than through a bright foreground of atmospheric and telescope emissions. IRAS carried out a rapid but comprehensive survey of the entire infrared sky over a 10-month period, cataloging about 350,000 sources of infrared radiation. Since then, several other infrared telescopes have operated in space with much better sensitivity and resolution due to improvements in infrared detectors. The most powerful of these infrared telescopes is the 0.85-meter Spitzer Space Telescope, which launched in 2003. A few of its observations are shown in Figure 6.24. With infrared observations, astronomers can detect cooler parts of cosmic objects, such as the dust clouds around star nurseries and the remnants of dying stars, that visible-light images don't reveal.

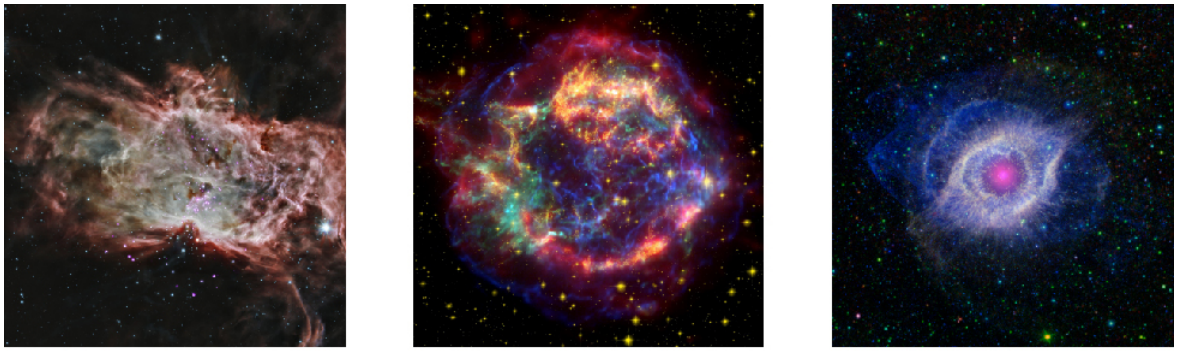


Figure 6.24 : Observations from the Spitzer Space Telescope (SST). These infrared images—a region of star formation, the remnant of an exploded star, and a region where an old star is losing its outer shell—show just a few of the observations made and transmitted back to Earth from the SST. Since our eyes are not sensitive to infrared rays, we don't perceive colors from them. The colors in these images have been selected by astronomers to highlight details like the composition or temperature in these regions. (credit "Flame nebula": modification of work by NASA (X-ray: NASA/CXC/PSU/K.Getman, E.Feigelson, M.Kuhn & the MYStIX team; Infrared:NASA/JPL-Caltech); credit "Cassiopeia A": modification of work by NASA/JPL-Caltech; credit "Helix nebula": modification of work by NASA/JPL-Caltech)

Hubble Space Telescope

In April 1990, a great leap forward in astronomy was made with the launch of the Hubble Space Telescope (HST). With an aperture of 2.4 meters, this is the largest telescope put into space so far. (Its aperture was limited by the size of the payload bay in the Space Shuttle that served as its launch vehicle.) It was named for Edwin Hubble, the astronomer who discovered the expansion of the universe in the 1920s (whose work we will discuss in the chapters on Galaxies).

HST is operated jointly by NASA's Goddard Space Flight Center and the Space Telescope Science Institute in Baltimore. It was the first orbiting observatory designed to be serviced by Shuttle astronauts and, over the years since it was launched, they made several visits to improve or replace its initial instruments and to repair some of the systems that operate the spacecraft (Figure 6.1)—though this repair program has now been discontinued, and no more visits or improvements will be made.

With the Hubble, astronomers have obtained some of the most detailed images of astronomical objects from the solar system outward to the most distant galaxies. Among its many great achievements is the Hubble Ultra-Deep Field, an image of a small region of the sky observed for almost 100 hours. It contains views of about 10,000 galaxies, some of which formed when the universe was just a few percent of its current age (Figure 6.25).



Figure 6.25 : Hubble Ultra-Deep Field (HUDF). The Hubble Space Telescope has provided an image of a specific region of space built from data collected between September 24, 2003, and January 16, 2004. These data allow us to search for galaxies that existed approximately 13 billion years ago. (credit: modification of work by NASA)

The HST's mirror was ground and polished to a remarkable degree of accuracy. If we were to scale up its 2.4-meter mirror to the size of the entire continental United States, there would be no hill or valley larger than about 6 centimeters in its smooth surface. Unfortunately, after it was launched, scientists discovered that the primary mirror had a slight error in its *shape*, equal to roughly 1/50 the width of a human hair. Small as that sounds, it was enough to ensure that much of the light entering the telescope did not come to a clear focus and that all the images were blurry. (In a misplaced effort to save money, a complete test of the optical system had not been carried out before launch, so the error was not discovered until HST was in orbit.)

The solution was to do something very similar to what we do for astronomy students with blurry vision: put corrective optics in front of their eyes. In December 1993, in one of the most exciting and difficult space missions ever flown, astronauts captured the orbiting telescope and brought it back into the shuttle payload bay. There they installed a package containing compensating optics as well as a new, improved camera before releasing HST back into orbit. The telescope now works as it was intended to, and further missions to it were able to install even more advanced instruments to take advantage of its capabilities.

High-Energy Observatories

Ultraviolet, X-ray, and direct gamma-ray (high-energy electromagnetic wave) observations can be made only from space. Such observations first became possible in 1946, with V2 rockets captured from Germany after World War II. The US Naval Research Laboratory put instruments on these rockets for a series of pioneering flights, used initially to detect ultraviolet radiation from the Sun. Since then, many other rockets have been launched to make X-ray and ultraviolet observations of the Sun, and later of other celestial objects.

Beginning in the 1960s, a steady stream of high-energy observatories has been launched into orbit to reveal and explore the universe at short wavelengths. Among recent X-ray telescopes is the Chandra X-ray Observatory, which was launched in 1999 (Figure 6.26). It is producing X-ray images with unprecedented resolution and sensitivity. Designing instruments that can collect and focus energetic radiation like X-rays and gamma rays is an enormous technological challenge. The 2002 Nobel Prize in physics was awarded to Riccardo Giacconi, a pioneer in the field of building and launching sophisticated X-ray instruments. In 2008, NASA launched the Fermi Gamma-ray Space Telescope, designed to measure cosmic gamma rays at energies greater than any previous telescope, and thus able to collect radiation from some of the most energetic events in the universe.

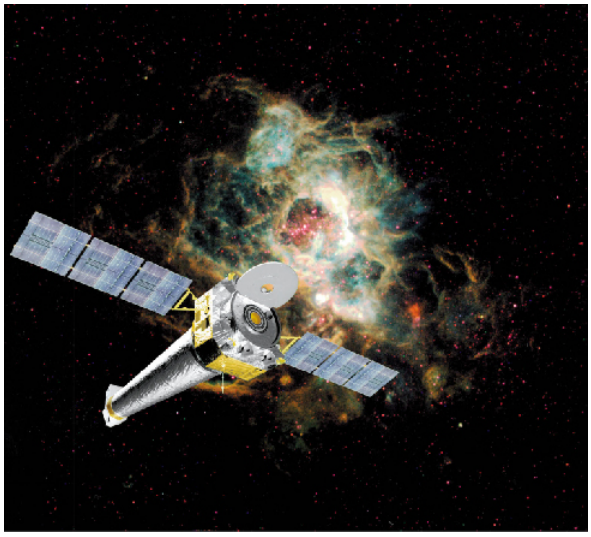


Figure 6.26 : Chandra X-Ray Satellite. Chandra, the world's most powerful X-ray telescope, was developed by NASA and launched in July 1999. (credit: modification of work by NASA)

One major challenge is to design "mirrors" to reflect such penetrating radiation as X-rays and gamma rays, which normally pass straight through matter. However, although the technical details of design are more complicated, the three basic components of an observing system, as we explained earlier in this chapter, are the same at all wavelengths: a telescope to gather up the radiation, filters or instruments to sort the radiation according to wavelength, and some method of detecting and making a permanent record of the observations. Table 6.4 lists some of the most important active space observatories that humanity has launched.

Gamma-ray detections can also be made from Earth's surface by using the atmosphere as the primary detector. When a gamma ray hits our atmosphere, it accelerates charged particles (mostly electrons) in the atmosphere. Those energetic particles hit other particles in the atmosphere and give off their own radiation. The effect is a cascade of light and energy that can be detected on the ground. The VERITAS array in Arizona and the H.E.S.S. array in Namibia are two such ground-based gamma-ray observatories.

Table 6.4: Recent Observatories in Space

Observatory	Date Operation Began	Bands of the Spectrum	Notes	Website
Hubble Space Telescope (HST)	1990	visible, UV, IR	2.4-m mirror; images and spectra	www.hubblesite.org
Chandra X-Ray Observatory	1999	X-rays	X-ray images and spectra	www.chandra.si.edu
XMM-Newton	1999	X-rays	X-ray spectroscopy	http://www.cosmos.esa.int/web/xmm-newton
International Gamma-Ray Astrophysics Laboratory (INTEGRAL)	2002	X- and gamma-rays	higher resolution gamma-ray images	http://sci.esa.int/integral/
Spitzer Space Telescope	2003	IR	0.85-m telescope	www.spitzer.caltech.edu

Observatory	Date Operation Began	Bands of the Spectrum	Notes	Website
Fermi Gamma-ray Space Telescope	2008	gamma-rays	first high-energy gamma-ray observations	fermi.gsfc.nasa.gov
Kepler	2009	visible-light	planet finder	kepler.nasa.gov
Wide-field Infrared Survey Explorer (WISE)	2009	IR	whole-sky map, asteroid searches	www.nasa.gov/mission_pages/WISE/main
Gaia	2013	visible-light	Precise map of the Milky Way	http://sci.esa.int/gaia/
Transiting Exoplanet Survey Satellite (TESS)	2018	visible-light	Planet finder	http://tess.mit.edu

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6.7: The Future of Large Telescopes

Learning Objectives

By the end of this section, you will be able to:

- Describe the next generation of ground- and space-based observatories
- Explain some of the challenges involved in building these observatories

If you've ever gone on a hike, you have probably been eager to see what lies just around the next bend in the path. Researchers are no different, and astronomers and engineers are working on the technologies that will allow us to explore even more distant parts of the universe and to see them more clearly.

The premier space facility planned for the next decade is the James Webb Space Telescope (Figure 6.27), which was launched on December 25, 2021. James Webb was one of the early administrators in NASA. As we write this (in December 2021), the telescope is on its way to a stable orbit point, some 1.5 million kilometers from Earth (where no astronauts can currently travel if the facility needs repair). During its 29-day journey, a number of activities must be successfully executed in order to prepare the JWST to make observations. A solar array will be deployed to provide energy, and a sunshield will be stretched out to protect the telescope from the intense heat of the Sun. The secondary and primary mirrors will then be unfolded. The primary mirror is 6 meters in diameter, made up, like the Keck telescopes, of 36 small hexagons. JWST has been designed to operate at infrared wavelengths and will have the sensitivity needed to detect the very first generation of stars, formed when the universe was only a few hundred million years old.

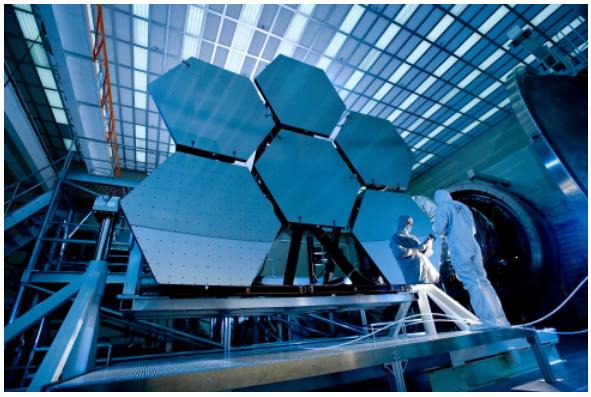


Figure 6.27 : James Webb Space Telescope (JWST). This image shows some of the mirrors of the JWST as they underwent cryogenic testing. The mirrors were exposed to extreme temperatures in order to gather accurate measurements on changes in their shape as they heated and cooled. (credit: NASA/MSFC/David Higginbotham/Emmett Given)

Link to Learning

Watch this video to learn more about the James Webb Space Telescope and how it will build upon the work that Hubble has allowed us to begin in exploring the universe. Visit NASA's James Webb Space Telescope site to keep track of how the JWST is doing.

On the ground, astronomers have started building the Vera Rubin Observatory[1], which has an 8.4-meter telescope with a significantly larger field of view than any existing telescopes. It will rapidly scan the sky to find *transients*, phenomena that change quickly, such as exploding stars and chunks of rock that orbit near Earth. It is expected to see first light in 2022.

The international gamma-ray community is planning the Cherenkov Telescope Array (CTA), two arrays of telescopes, one in each hemisphere, which will indirectly measure gamma rays from the ground. The CTA will measure gamma-ray energies a thousand times as great as the Fermi telescope can detect.

Several groups of astronomers around the globe interested in studying visible light and the infrared are exploring the feasibility of building ground-based telescopes with mirrors larger than 30 meters across. Stop and think what this means: 30 meters is one-third the length of a football field. It is technically impossible to build and transport a single astronomical mirror that is 30 meters or

larger in diameter. The primary mirror of these giant telescopes will consist of smaller mirrors, all aligned so that they act as a very large mirror in combination.

The most ambitious of these projects is the European Extremely Large Telescope (ELT) (Figure 6.28). (Astronomers try to outdo each other not only with the size of these telescopes, but also their names!) The design of the European ELT calls for a 39.3-meter primary mirror, which will follow the Keck design and be made up of 798 hexagonal mirrors, each 1.4 meters in diameter and all held precisely in position so that they form a continuous surface. Construction on the site in the Atacama Desert in Northern Chile started in 2014, and operations are expected to begin in about 2025.

International consortia with major contributions from U.S. astronomers have developed plans for the construction of two large new telescopes. One is a Thirty-Meter Telescope (TMT) for which the preferred site is Maunakea in Hawaii. The design of this telescope is similar to that of the European ELT and will make use of 492 hexagonal elements. Each segment is about 1.44 meters (56.6 inches) across corners. The segments are closely spaced, with gaps between the segments only 2.5 mm (0.1 inch) wide.

The Giant Magellan Telescope (GMT) is the second ELT project with major participation by U.S. astronomers. The GMT is also a segmented mirror telescope that employs seven stiff monolith 8.4-meter mirrors as segments. Construction has started at the selected site, which is near the Las Campanas Observatory on the southern edge of the Atacama Desert.

These giant telescopes will combine light-gathering power with high-resolution imaging. These powerful new instruments will enable astronomers to tackle many important astronomical problems. As just one example, they provide us images and spectra of planets around other stars and thus, perhaps, give us the first real evidence (from the chemistry of these planets' atmospheres) that life exists elsewhere.

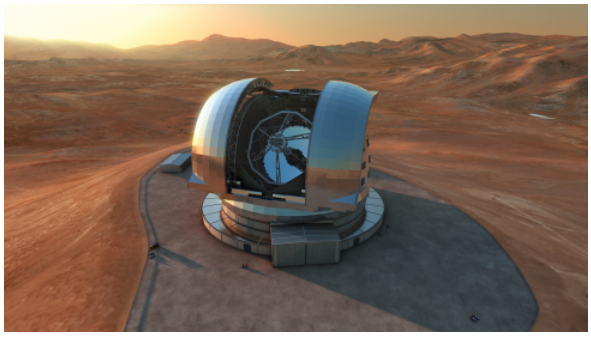


Figure 6.28 : Artist's Conception of the European Extremely Large Telescope. The primary mirror in this telescope is 39.3 meters across. The telescope is under construction in the Atacama Desert in Northern Chile. (credit: ESO/L. Calçada)

Link to Learning

Check out this fun diagram comparing the sizes of the largest planned and existing telescopes to a regulation basketball and tennis court.

Footnotes

- 1The observatory is named after the American astronomer whose work led us to the understanding that much of the universe is made of a mysterious substance that scientists call dark matter (which we explain in The Mass of the Galaxy).

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6.8: Key Terms

adaptive optics
systems used with telescopes that can compensate for distortions in an image introduced by the atmosphere, thus resulting in sharper images

aperture
diameter of the primary lens or mirror of a telescope

charge-coupled device (CCD)
array of high-sensitivity electronic detectors of electromagnetic radiation, used at the focus of a telescope (or camera lens) to record an image or spectrum

chromatic aberration
distortion that causes an image to appear fuzzy when each wavelength coming into a transparent material focuses at a different spot

detector
device sensitive to electromagnetic radiation that makes a record of astronomical observations

eyepiece
magnifying lens used to view the image produced by the objective lens or primary mirror of a telescope

focus
(of telescope) point where the rays of light converged by a mirror or lens meet

interference
process in which waves mix together such that their crests and troughs can alternately reinforce and cancel one another

interferometer
instrument that combines electromagnetic radiation from one or more telescopes to obtain a resolution equivalent to what would be obtained with a single telescope with a diameter equal to the baseline separating the individual separate telescopes

interferometer array
combination of multiple radio dishes to, in effect, work like a large number of two-dish interferometers

prime focus
point in a telescope where the objective lens or primary mirror focuses the light

radar
technique of transmitting radio waves to an object and then detecting the radiation that the object reflects back to the transmitter; used to measure the distance to, and motion of, a target object or to form images of it

reflecting telescope
telescope in which the principal light collector is a concave mirror

refracting telescope
telescope in which the principal light collector is a lens or system of lenses

resolution
detail in an image; specifically, the smallest angular (or linear) features that can be distinguished

seeing
unsteadiness of Earth’s atmosphere, which blurs telescopic images; good seeing means the atmosphere is steady

telescope

instrument for collecting visible-light or other electromagnetic radiation

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6.9: Summary

6.1 Telescopes

A telescope collects the faint light from astronomical sources and brings it to a focus, where an instrument can sort the light according to wavelength. Light is then directed to a detector, where a permanent record is made. The light-gathering power of a telescope is determined by the diameter of its aperture, or opening—that is, by the area of its largest or primary lens or mirror. The primary optical element in a telescope is either a convex lens (in a refracting telescope) or a concave mirror (in a reflector) that brings the light to a focus. Most large telescopes are reflectors; it is easier to manufacture and support large mirrors because the light does not have to pass through glass.

6.2 Telescopes Today

New technologies for creating and supporting lightweight mirrors have led to the construction of a number of large telescopes since 1990. The site for an astronomical observatory must be carefully chosen for clear weather, dark skies, low water vapor, and excellent atmospheric seeing (low atmospheric turbulence). The resolution of a visible-light or infrared telescope is degraded by turbulence in Earth's atmosphere. The technique of adaptive optics, however, can make corrections for this turbulence in real time and produce exquisitely detailed images.

6.3 Visible-Light Detectors and Instruments

Visible-light detectors include the human eye, photographic film, and charge-coupled devices (CCDs). Detectors that are sensitive to infrared radiation must be cooled to very low temperatures since everything in and near the telescope gives off infrared waves. A spectrometer disperses the light into a spectrum to be recorded for detailed analysis.

6.4 Radio Telescopes

In the 1930s, radio astronomy was pioneered by Karl G. Jansky and Grote Reber. A radio telescope is basically a radio antenna (often a large, curved dish) connected to a receiver. Significantly enhanced resolution can be obtained with interferometers, including interferometer arrays like the 27-element VLA and the 66-element ALMA. Expanding to very long baseline interferometers, radio astronomers can achieve resolutions as precise as 0.0001 arcsecond. Radar astronomy involves transmitting as well as receiving. The largest radar telescope currently in operation is a 305-meter bowl at Arecibo.

6.5 Observations outside Earth's Atmosphere

Infrared observations are made with telescopes aboard aircraft and in space, as well as from ground-based facilities on dry mountain peaks. Ultraviolet, X-ray, and gamma-ray observations must be made from above the atmosphere. Many orbiting observatories have been flown to observe in these bands of the spectrum in the last few decades. The largest-aperture telescope in space is the Hubble Space telescope (HST), the most significant infrared telescope is Spitzer, and Chandra and Fermi are the premier X-ray and gamma-ray observatories, respectively.

6.6 The Future of Large Telescopes

New and even larger telescopes are on the drawing boards. The James Webb Space Telescope, a 6-meter successor to Hubble, is currently scheduled for launch in 2021. Gamma-ray astronomers are planning to build the CTA to measure very energetic gamma rays. Astronomers are building the LSST to observe with an unprecedented field of view and a new generation of visible-light/infrared telescopes with apertures of 24.5 to 39 meters in diameter.

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6.10: For Further Exploration

Articles

Blades, J. C. “Fixing the Hubble One Last Time.” *Sky & Telescope* (October 2008): 26. On the last Shuttle service mission and what the Hubble was then capable of doing.

Brown, A. “How Gaia will Map a Billion Stars.” *Astronomy* (December 2014): 32. Nice review of the mission to do photometry and spectroscopy of all stars above a certain brightness.

Irion, R. “Prime Time.” *Astronomy* (February 2001): 46. On how time is allotted on the major research telescopes.

Jedicke, Peter & Robert. “The Coming Giant Sky Patrols.” *Sky & Telescope* (September 2008): 30. About giant telescopes to survey the sky continuously.

Lazio, Joseph, et al. “Tuning in to the Universe: 21st Century Radio Astronomy.” *Sky & Telescope* (July 2008): 21. About ALMA and the Square Kilometer Array.

Lowe, Jonathan. “Mirror, Mirror.” *Sky & Telescope* (December 2007): 22. On the Large Binocular Telescope in Arizona.

Lowe, Jonathan. “Next Light: Tomorrow’s Monster Telescopes.” *Sky & Telescope* (April 2008): 20. About plans for extremely large telescopes on the ground.

Mason, Todd & Robin. “Palomar’s Big Eye.” *Sky & Telescope* (December 2008): 36. On the Hale 200-inch telescope.

Subinsky, Raymond. “Who Really Invented the Telescope.” *Astronomy* (August 2008): 84. Brief historical introduction, focusing on Hans Lippershey.

Young, Monica “The New Space Race (and Problem).” *Sky & Telescope* (March 2020): 14. A good discussion of the danger that huge numbers of new reflective satellites (to provide Wi-Fi) poses to the darkness of the night sky for astronomers.

Websites

Websites for major telescopes are given in Table 6.1, Table 6.2, Table 6.3, and Table 6.4.

Information on Swarms of Satellites on Low-Earth Orbit

- American Astronomical Society page on the issue with updates and links: aas.org/posts/advocacy/2020/12/impacts-large-satellite-constellations-astronomy-live-updates
- Lawler, S. “Space-X’s Starlink Satellites are About to Ruin Stargazing Forever” on the *Astronomy* magazine website (November 25, 2020): https://astronomy.com/news/2020/11/spacexs-starlink-satellites-are-about-to-ruin-stargazing-for-everyone
- Patel, N. “Satellite Mega-constellations Risk Ruining Astronomy Forever” in *Technology Review*, September 2, 2020: https://www.technologyreview.com/2020/09/02/1007938/satellite-mega-constellations-risk-ruining-astronomy-forever/

Videos

Astronomy from the Stratosphere: SOFIA: https://www.youtube.com/watch?v=NV98BcBBA9c. A talk by Dr. Dana Backman (1:15:32)

Galaxies Viewed in Full Spectrum of Light: https://www.youtube.com/watch?v=368K0iQv8nE. Scientists with the Spitzer Observatory show how a galaxy looks different at different wavelengths (6:22)

Lifting the Cosmic Veil: Highlights from a Decade of the Spitzer Space Telescope: https://www.youtube.com/watch?v=nkrNQcwkY78. A talk by Dr. Michael Bicay (1:42:44)

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6.11: Collaborative Group Activities

A. Most large telescopes get many more proposals for observing projects than there is night observing time available in a year. Suppose your group is the telescope time allocation committee reporting to an observatory director. What criteria would you use in deciding how to give out time on the telescope? What steps could you take to make sure all your colleagues thought the process was fair and people would still talk to you at future astronomy meetings?

B. Your group is a committee of nervous astronomers about to make a proposal to the government ministers of your small European country to chip in with other countries to build the world's largest telescope in the high, dry desert of the Chilean Andes Mountains. You expect the government ministers to be very skeptical about supporting this project. What arguments would you make to convince them to participate?

C. The same government ministers we met in the previous activity ask you to draw up a list of the pros and cons of having the world's largest telescope in the mountains of Chile (instead of a mountain in Europe). What would your group list in each column?

D. Your group should discuss and make a list of all the ways in which an observing session at a large visible-light telescope and a large radio telescope might differ. (Hint: Bear in mind that because the Sun is not especially bright at many radio wavelengths, observations with radio telescopes can often be done during the day.)

E. Another "environmental threat" to astronomy (besides light pollution) comes from the spilling of terrestrial communications into the "channels"—wavelengths and frequencies—previously reserved for radio astronomy. For example, the demand for cellular phones means that more and more radio channels will be used for this purpose. The faint signals from cosmic radio sources could be drowned in a sea of earthly conversation (translated and sent as radio waves). Assume your group is a congressional committee being lobbied by both radio astronomers, who want to save some clear channels for doing astronomy, and the companies that stand to make a lot of money from expanding cellular phone use. What arguments would sway you to each side?

F. When the site for the new Thirty-Meter Telescope on Hawaii's Maunakea was dedicated, a group of native Hawaiians announced opposition to the project because astronomers were building too many telescopes on a mountain that native Hawaiians consider a sacred site. You can read more about this controversy at www.nytimes.com/2015/12/04/sc...cope.html?_r=0 and at http://www.nature.com/news/the-mount...escope-1.18446. Once your group has the facts, discuss the claims of each side in the controversy. How do you think it should be resolved?

G. If you could propose to use a large modern telescope, what would you want to find out? What telescope would you use and why?

H. Light pollution (spilled light in the night sky making it difficult to see the planets and stars) used to be an issue that concerned mostly astronomers. Now spilled light at night is also of concern to environmentalists and those worrying about global warming. Can your group come up with some non-astronomical reasons to be opposed to light pollution?

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CHAPTER OVERVIEW

6.12: Exercises

6.12.1: Review Questions

6.12.2: Thought Questions

6.12.3: Figuring for Yourself

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6.12.1: Review Questions

Review Questions

1.

What are the three basic components of a modern astronomical instrument? Describe each in one to two sentences.

2.

Name the two spectral windows through which electromagnetic radiation easily reaches the surface of Earth and describe the largest-aperture telescope currently in use for each window.

3.

List the largest-aperture single telescope currently in use in each of the following bands of the electromagnetic spectrum: radio, X-ray, gamma ray.

4.

When astronomers discuss the apertures of their telescopes, they say bigger is better. Explain why.

5.

The Hooker telescope at Palomar Observatory has a diameter of 5 m, and the Keck I telescope has a diameter of 10 m. How much more light can the Keck telescope collect than the Hooker telescope in the same amount of time?

6.

What is meant by “reflecting” and “refracting” telescopes?

7.

Why are the largest visible-light telescopes in the world made with mirrors rather than lenses?

8.

Compare the eye, photographic film, and CCDs as detectors for light. What are the advantages and disadvantages of each?

9.

What is a charge-coupled device (CCD), and how is it used in astronomy?

10.

Why is it difficult to observe at infrared wavelengths? What do astronomers do to address this difficulty?

11.

Radio and radar observations are often made with the same antenna, but otherwise they are very different techniques. Compare and contrast radio and radar astronomy in terms of the equipment needed, the methods used, and the kind of results obtained.

12.

Look back at Figure 6.18 of Cygnus A and read its caption again. The material in the giant lobes at the edges of the image had to have been ejected from the center *at least* how many years ago?

13.

Why do astronomers place telescopes in Earth’s orbit? What are the advantages for the different regions of the spectrum?

14.

What was the problem with the Hubble Space Telescope and how was it solved?

15.

Describe the techniques radio astronomers use to obtain a resolution comparable to what astronomers working with visible light can achieve.

16.

What kind of visible-light and infrared telescopes on the ground are astronomers planning for the future? Why are they building them on the ground and not in space?

17.

Describe one visible-light or infrared telescope that astronomers are planning to launch into space in the future.

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6.12.2: Thought Questions

Thought Questions

18.

What happens to the image produced by a lens if the lens is “stopped down” (the aperture reduced, thereby reducing the amount of light passing through the lens) with an iris diaphragm—a device that covers its periphery?

19.

What would be the properties of an ideal astronomical detector? How closely do the actual properties of a CCD approach this ideal?

20.

Many decades ago, the astronomers on the staff of Mount Wilson and Palomar Observatories each received about 60 nights per year for their observing programs. Today, an astronomer feels fortunate to get 10 nights per year on a large telescope. Can you suggest some reasons for this change?

21.

The largest observatory complex in the world is on Maunakea, the tallest mountain on Earth. What are some factors astronomers consider when selecting an observatory site? Don’t forget practical ones. Should astronomers, for example, consider building an observatory on Denali (Mount McKinley) or Mount Everest?

22.

Suppose you are looking for sites for a visible-light observatory, an infrared observatory, and a radio observatory. What are the main criteria of excellence for each? What sites are actually considered the best today?

23.

Radio astronomy involves wavelengths much longer than those of visible light, and many orbiting observatories have probed the universe for radiation of very short wavelengths. What sorts of objects and physical conditions would you expect to be associated with emission of radiation at very long and very short wavelengths?

24.

The dean of a university located near the ocean (who was not a science major in college) proposes building an infrared telescope right on campus and operating it in a nice heated dome so that astronomers will be comfortable on cold winter nights. Criticize this proposal, giving your reasoning.

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6.12.3: Figuring for Yourself

Figuring for Yourself

25.

What is the area, in square meters, of a 10-m telescope?

26.

Approximately 9000 stars are visible to the naked eye in the whole sky (imagine that you could see around the entire globe and both the northern and southern hemispheres), and there are about 41,200 square degrees on the sky. How many stars are visible per square degree? Per square arcsecond?

27.

Theoretically (that is, if seeing were not an issue), the resolution of a telescope is inversely proportional to its diameter. How much better is the resolution of the ALMA when operating at its longest baseline than the resolution of the Arecibo telescope?

28.

In broad daylight, the size of your pupil is typically 3 mm. In dark situations, it expands to about 7 mm. How much more light can it gather?

29.

How much more light can be gathered by a telescope that is 8 m in diameter than by your fully dark-adapted eye at 7 mm?

30.

How much more light can the Keck telescope (with its 10-m diameter mirror) gather than an amateur telescope whose mirror is 25 cm (0.25 m) across?

31.

People are often bothered when they discover that reflecting telescopes have a second mirror in the middle to bring the light out to an accessible focus where big instruments can be mounted. “Don’t you lose light?” people ask. Well, yes, you do, but there is no better alternative. You can estimate how much light is lost by such an arrangement. The primary mirror (the one at the bottom in Figure 6.6) of the Gemini North telescope is 8 m in diameter. The secondary mirror at the top is about 1 m in diameter. Use the formula for the area of a circle to estimate what fraction of the light is blocked by the secondary mirror.

32.

Telescopes can now be operated remotely from a warm room, but until about 25 years ago, astronomers worked at the telescope to guide it so that it remained pointed in exactly the right place. In a large telescope, like the Palomar 200-inch telescope, astronomers sat in a cage at the top of the telescope, where the secondary mirror is located, as shown in Figure 6.6. Assume for the purpose of your calculation that the diameter of this cage was 40 inches. What fraction of the light is blocked?

33.

The HST cost about $1.7 billion for construction and $300 million for its shuttle launch, and it costs $250 million per year to operate. If the telescope lasts for 20 years, what is the total cost per year? Per day? If the telescope can be used just 30% of the time for actual observations, what is the cost per hour and per minute for the astronomer’s observing time on this instrument? What is the cost per person in the United States? Was your investment in the Hubble Space telescope worth it?

34.

How much more light can the James Webb Space Telescope (with its 6-m diameter mirror) gather than the Hubble Space Telescope (with a diameter of 2.4 m)?

35.

The Palomar telescope’s 5-m mirror weighs 14.5 tons. If a 10-m mirror were constructed of the same thickness as Palomar’s (only bigger), how much would it weigh?

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CHAPTER OVERVIEW

7: Earth as a Planet

Airless worlds in our solar system seem peppered with craters large and small. Earth, on the other hand, has few craters, but a thick atmosphere and much surface activity. Although impacts occurred on Earth at the same rate, craters have since been erased by forces in the planet's crust and atmosphere. What can the comparison between the obvious persistent cratering on so many other worlds, and the different appearance of Earth, tell us about the history of our planet?

As our first step in exploring the solar system in more detail, we turn to the most familiar planet, our own Earth. The first humans to see Earth as a blue sphere floating in the blackness of space were the astronauts who made the first voyage around the Moon in 1968. For many people, the historic images showing our world as a small, distant globe represent a pivotal moment in human history, when it became difficult for educated human beings to view our world without a global perspective. In this chapter, we examine the composition and structure of our planet with its envelope of ocean and atmosphere. We ask how our terrestrial environment came to be the way it is today, and how it compares with other planets.

7.1: Thinking Ahead
7.2: The Global Perspective
7.3: Earth's Crust
7.4: Earth's Atmosphere
7.5: Life, Chemical Evolution, and Climate Change
7.6: Cosmic Influences on the Evolution of Earth
7.7: Key Terms
7.8: Summary
7.9: For Further Exploration
7.10: Collaborative Group Activities
7.11: Exercises
7.11.1: Review Questions
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7.11.3: Figuring for Yourself

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7.1: Thinking Ahead



Figure 8.1 : Active Geology. This image, taken from the International Space Station in 2006, shows a plume of ash coming from the Cleveland Volcano in the Aleutian Islands. Although the plume was only visible for around two hours, such events are a testament to the dynamic nature of Earth's crust. (credit: modification of work by NASA)

Airless worlds in our solar system seem peppered with craters large and small. Earth, on the other hand, has few craters, but a thick atmosphere and much surface activity. Although impacts occurred on Earth at the same rate, craters have since been erased by forces in the planet's crust and atmosphere. What can the comparison between the obvious persistent cratering on so many other worlds, and the different appearance of Earth, tell us about the history of our planet?

As our first step in exploring the solar system in more detail, we turn to the most familiar planet, our own Earth. The first humans to see Earth as a blue sphere floating in the blackness of space were the astronauts who made the first voyage around the Moon in 1968. For many people, the historic images showing our world as a small, distant globe represent a pivotal moment in human history, when it became difficult for educated human beings to view our world without a global perspective. In this chapter, we examine the composition and structure of our planet with its envelope of ocean and atmosphere. We ask how our terrestrial environment came to be the way it is today, and how it compares with other planets.

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7.2: The Global Perspective

Learning Objectives

By the end of this section, you will be able to:

- Describe the components of Earth's interior and explain how scientists determined its structure
- Specify the origin, size, and extent of Earth's magnetic field

Earth is a medium-size planet with a diameter of approximately 12,760 kilometers (Figure 8.2). As one of the inner or terrestrial planets, it is composed primarily of heavy elements such as iron, silicon, and oxygen—very different from the composition of the Sun and stars, which are dominated by the light elements hydrogen and helium. Earth's orbit is nearly circular, and Earth is warm enough to support liquid water on its surface. It is the only planet in our solar system that is neither too hot nor too cold, but "just right" for the development of life as we know it. Some of the basic properties of Earth are summarized in Table 8.1.



Figure 8.2 : Blue Marble. This image of Earth from space, taken by the Apollo 17 astronauts, is known as the "Blue Marble." This is one of the rare images of a full Earth taken during the Apollo program; most images show only part of Earth's disk in sunlight. (credit: modification of work by NASA)

Table 8.1: Some Properties of Earth

Property	Measurement
Semimajor axis	1.00 AU
Period	1.00 year
Mass	5.98×10^{24} kg
Diameter	12,756 km
Radius	6378 km
Escape velocity	11.2 km/s
Rotational period	23 h 56 m 4 s
Surface area	5.1×10^{8} km^2
Density	5.514 g/cm^3
Atmospheric pressure	1.00 bar

Earth's Interior

The interior of a planet—even our own Earth—is difficult to study, and its composition and structure must be determined indirectly. Our only direct experience is with the outermost skin of Earth's crust, a layer no more than a few kilometers deep. It is important to remember that, in many ways, we know less about our own planet 5 kilometers beneath our feet than we do about the surfaces of Venus and Mars.

Earth is composed largely of metal and silicate rock (see the Composition and Structure of Planets section). Most of this material is in a solid state, but some of it is hot enough to be molten. The structure of material in Earth's interior has been probed in considerable detail by measuring the transmission of seismic waves through Earth. These are waves that spread through the interior of Earth from earthquakes or explosion sites.

Seismic waves travel through a planet rather like sound waves through a struck bell. Just as the sound frequencies vary depending on the material the bell is made of and how it is constructed, so a planet's response depends on its composition and structure. By monitoring the seismic waves in different locations, scientists can learn about the layers through which the waves have traveled. Some of these vibrations travel along the surface; others pass directly through the interior. Seismic studies have shown that Earth's interior consists of several distinct layers with different compositions, illustrated in Figure 8.3. As waves travel through different materials in Earth's interior, the waves—just like light waves in telescope lenses—bend (or refract) so that some seismic stations on Earth receive the waves and others are in "shadows." Detecting the waves in a network of seismographs helps scientists construct a model of Earth's interior, showing liquid and solid layers. This type of seismic imaging is not unlike that used in ultrasound, a type of imaging used to see inside the body.

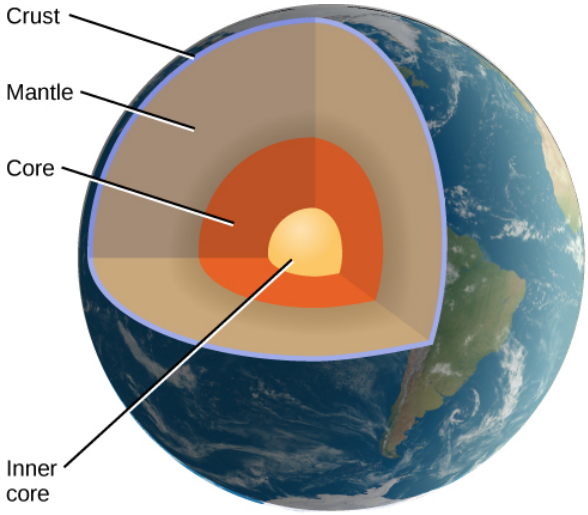


Figure 8.3 : Interior Structure of Earth. The crust, mantle, and inner and outer cores (solid and liquid, respectively) as shown as revealed by seismic studies.

The top layer is the crust, the part of Earth we know best (Figure 8.4). Oceanic crust covers 55% of Earth's surface and lies mostly submerged under the oceans. It is typically about 6 kilometers thick and is composed of volcanic rocks called basalt. Produced by the cooling of volcanic lava, basalts are made primarily of the elements silicon, oxygen, iron, aluminum, and magnesium. The continental crust covers 45% of the surface, some of which is also beneath the oceans. The continental crust is 20 to 70 kilometers thick and is composed predominantly of a different volcanic class of silicates (rocks made of silicon and oxygen) called granite. These crustal rocks, both oceanic and continental, typically have densities of about 3 g/cm^3. (For comparison, the density of water is 1 g/cm^3.) The crust is the easiest layer for geologists to study, but it makes up only about 0.3% of the total mass of Earth.

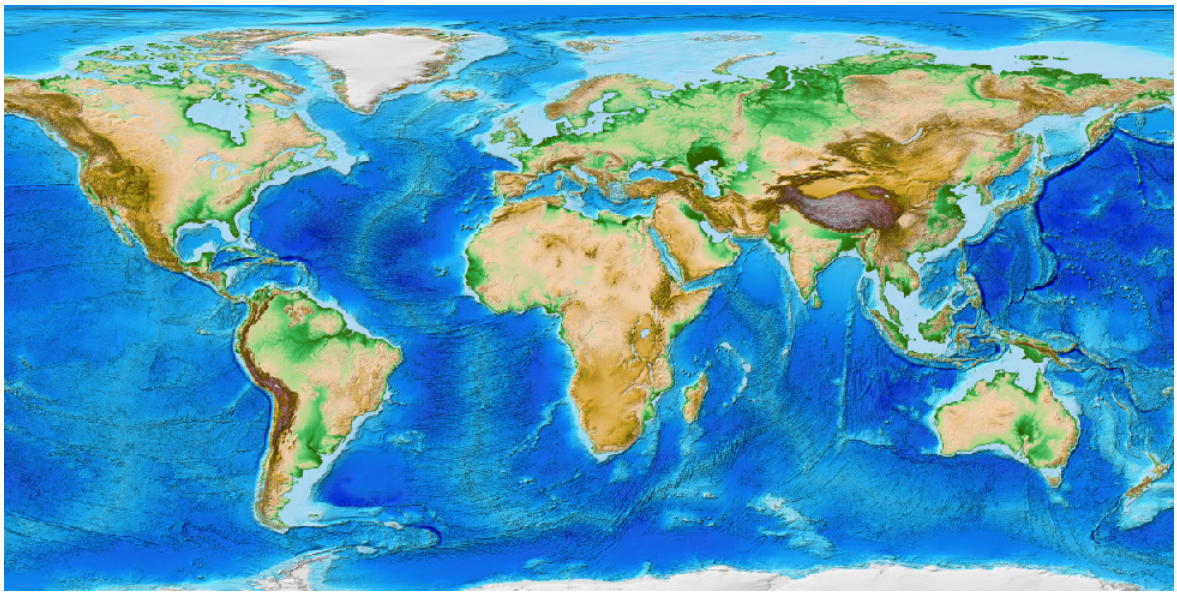


Figure 8.4 : Earth's Crust. This computer-generated image shows the surface of Earth's crust as determined from satellite images and ocean floor radar mapping. Oceans and lakes are shown in blue, with darker areas representing depth. Dry land is shown in shades of green and brown, and the Greenland and Antarctic ice sheets are depicted in shades of white. (credit: modification of work by C. Amante, B. W. Eakins, National Geophysical Data Center, NOAA)

The largest part of the solid Earth, called the mantle, stretches from the base of the crust downward to a depth of 2900 kilometers. The mantle is more or less solid, but at the temperatures and pressures found there, mantle rock can deform and flow slowly. The density in the mantle increases downward from about 3.5 g/cm^3 to more than 5 g/cm^3 as a result of the compression produced by the weight of overlying material. Samples of upper mantle material are occasionally ejected from volcanoes, permitting a detailed analysis of its chemistry.

Beginning at a depth of 2900 kilometers, we encounter the dense metallic core of Earth. With a diameter of 7000 kilometers, our core is substantially larger than the entire planet Mercury. The outer core is liquid, but the innermost part of the core (about 2400 kilometers in diameter) is probably solid. In addition to iron, the core probably also contains substantial quantities of nickel and sulfur, all compressed to a very high density.

The separation of Earth into layers of different densities is an example of *differentiation*, the process of sorting the major components of a planet by density. The fact that Earth is differentiated suggests that it was once warm enough for its interior to melt, permitting the heavier metals to sink to the center and form the dense core. Evidence for differentiation comes from comparing the planet's bulk density (5.5 g/cm^3) with the surface materials (3 g/cm^3) to suggest that denser material must be buried in the core.

Magnetic Field and Magnetosphere

We can find additional clues about Earth's interior from its magnetic field. Our planet behaves in some ways as if a giant bar magnet were inside it, aligned approximately with the rotational poles of Earth. This magnetic field is generated by moving material in Earth's liquid metallic core. As the liquid metal inside Earth circulates, it sets up a circulating electric current. When many charged particles are moving together like that—in the laboratory or on the scale of an entire planet—they produce a magnetic field.

Earth's magnetic field extends into surrounding space. When a charged particle encounters a magnetic field in space, it becomes trapped in the magnetic zone. Above Earth's atmosphere, our field is able to trap small quantities of electrons and other atomic particles. This region, called the magnetosphere, is defined as the zone within which Earth's magnetic field dominates over the weak interplanetary magnetic field that extends outward from the Sun (Figure 8.5).

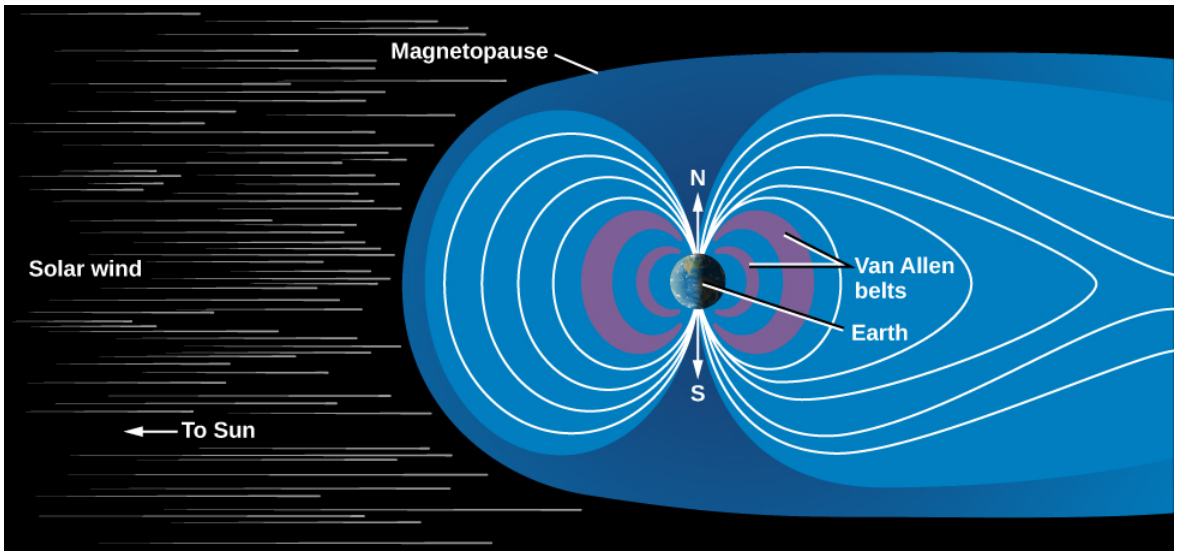


Figure 8.5 : Earth's Magnetosphere. A cross-sectional view of our magnetosphere (or zone of magnetic influence), as revealed by numerous spacecraft missions. Note how the wind of charged particles from the Sun "blows" the magnetic field outward like a wind sock.

Where do the charged particles trapped in our magnetosphere come from? They flow outward from the hot surface of the Sun; this is called the *solar wind*. It not only provides particles for Earth's magnetic field to trap, it also stretches our field in the direction pointing away from the Sun. Typically, Earth's magnetosphere extends about 60,000 kilometers, or 10 Earth radii, in the direction of the Sun. But, in the direction away from the Sun, the magnetic field can reach as far as the orbit of the Moon, and sometimes farther.

The magnetosphere was discovered in 1958 by instruments on the first US Earth satellite, *Explorer 1*, which recorded the ions (charged particles) trapped in its inner part. The regions of high-energy ions in the magnetosphere are often called the *Van Allen belts* in recognition of the University of Iowa professor who built the scientific instrumentation for *Explorer 1*. Since 1958, hundreds of spacecraft have explored various regions of the magnetosphere. You can read more about its interaction with the Sun in a later chapter.

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7.3: Earth's Crust

Learning Objectives

By the end of this section, you will be able to:

- Denote the primary types of rock that constitute Earth's crust
- Explain the theory of plate tectonics
- Describe the difference between rift and subduction zones
- Describe the relationship between fault zones and mountain building
- Explain the various types of volcanic activity occurring on Earth

Let us now examine our planet's outer layers in more detail. Earth's crust is a dynamic place. Volcanic eruptions, erosion, and large-scale movements of the continents rework the surface of our planet constantly. Geologically, ours is the most active planet. Many of the geological processes described in this section have taken place on other planets as well, but usually in their distant pasts. Some of the moons of the giant planets also have impressive activity levels. For example, Jupiter's moon Io has a remarkable number of active volcanoes.

Composition of the Crust

Earth's crust is largely made up of oceanic basalt and continental granite. These are both igneous rock, the term used for any rock that has cooled from a molten state. All volcanically produced rock is igneous (Figure 8.6).



Figure 8.6 : Formation of Igneous Rock as Liquid Lava Cools and Freezes. This is a lava flow from a basaltic eruption. Basaltic lava flows quickly and can move easily over distances of more than 20 kilometers. (credit: USGS)

Two other kinds of rock are familiar to us on Earth, although it turns out that neither is common on other planets. Sedimentary rocks are made of fragments of igneous rock or the shells of living organisms deposited by wind or water and cemented together without melting. On Earth, these rocks include the common sandstones, shales, and limestones. Metamorphic rocks are produced when high temperature or pressure alters igneous or sedimentary rock physically or chemically (the word *metamorphic* means "changed in form"). Metamorphic rocks are produced on Earth because geological activity carries surface rocks down to considerable depths and then brings them back up to the surface. Without such activity, these changed rocks would not exist at the surface.

There is a fourth very important category of rock that can tell us much about the early history of the planetary system: primitive rock, which has largely escaped chemical modification by heating. Primitive rock represents the original material out of which the planetary system was made. No primitive material is left on Earth because the entire planet was heated early in its history. To find primitive rock, we must look to smaller objects such as comets, asteroids, and small planetary moons. We can sometimes see primitive rock in samples that fall to Earth from these smaller objects.

A block of quartzite on Earth is composed of materials that have gone through all four of these states. Beginning as primitive material before Earth was born, it was heated in the early Earth to form igneous rock, transformed chemically and redeposited (perhaps many times) to form sedimentary rock, and finally changed several kilometers below Earth's surface into the hard, white metamorphic stone we see today.

Plate Tectonics

Geology is the study of Earth's crust and the processes that have shaped its surface throughout history. (Although *geo-* means "related to Earth," astronomers and planetary scientists also talk about the geology of other planets.) Heat escaping from the interior provides energy for the formation of our planet's mountains, valleys, volcanoes, and even the continents and ocean basins themselves. But not until the middle of the twentieth century did geologists succeed in understanding just how these landforms are created.

Plate tectonics is an idea that explains how slow motions within the mantle of Earth move large segments of the crust, resulting in a gradual "drifting" of the continents as well as the formation of mountains and other large-scale geological features. Plate tectonics is a concept as basic to geology as evolution by natural selection is to biology or gravity is to understanding the orbits of planets. Looking at it from a different perspective, plate tectonics is a mechanism for Earth to transport heat efficiently from the interior, where it has accumulated, out to space. It is a cooling system for the planet. All planets develop a heat transfer process as they evolve; mechanisms may differ from that on Earth as a result of chemical makeup and other constraints.

Earth's crust and upper mantle (to a depth of about 60 kilometers) are divided into about a dozen tectonic plates that fit together like the pieces of a jigsaw puzzle (Figure 8.7). In some places, such as the Atlantic Ocean, the plates are moving apart; in others, such as off the western coast of South America, they are being forced together. The power to move the plates is provided by slow convection of the mantle, a process by which heat escapes from the interior through the upward flow of warmer material and the slow sinking of cooler material. (Convection, in which energy is transported from a warm region, such as the interior of Earth, to a cooler region, such as the upper mantle, is a process we encounter often in astronomy—in stars as well as planets. It is also important in boiling water for coffee while studying for astronomy exams.)

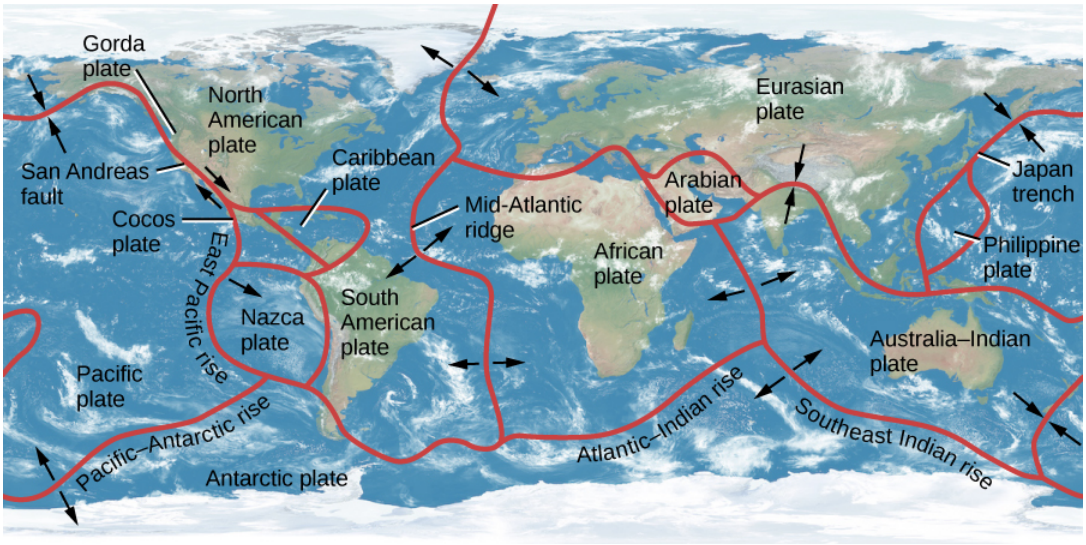


Figure 8.7 : Earth's Continental Plates. This map shows the major plates into which the crust of Earth is divided. Arrows indicate the motion of the plates at average speeds of 4 to 5 centimeters per year, similar to the rate at which your hair grows.

Link to Learning

The US Geological Survey provides a map of recent earthquakes and shows the boundaries of the tectonic plates and where earthquakes occur in relation to these boundaries. You can look close-up at the United States or zoom out for a global view.

As the plates slowly move, they bump into each other and cause dramatic changes in Earth's crust over time. Four basic kinds of interactions between crustal plates are possible at their boundaries: (1) they can pull apart, (2) one plate can burrow under another, (3) they can slide alongside each other, or (4) they can jam together. Each of these activities is important in determining the geology of Earth.

Voyagers in Astronomy: Alfred Wegener: Catching the Drift of Plate Tectonics

When studying maps or globes of Earth, many students notice that the coast of North and South America, with only minor adjustments, could fit pretty well against the coast of Europe and Africa. It seems as if these great landmasses could once have been together and then were somehow torn apart. The same idea had occurred to others (including Francis Bacon as early as 1620), but not until the twentieth century could such a proposal be more than speculation. The scientist who made the case for continental drift in 1920 was a German meteorologist and astronomer named Alfred Wegener (Figure 8.8).



Figure 8.8 : Alfred Wegener (1880–1930). Wegener proposed a scientific theory for the slow shifting of the continents.

Born in Berlin in 1880, Wegener was, from an early age, fascinated by Greenland, the world's largest island, which he dreamed of exploring. He studied at the universities in Heidelberg, Innsbruck, and Berlin, receiving a doctorate in astronomy by reexamining thirteenth-century astronomical tables. But, his interests turned more and more toward Earth, particularly its weather. He carried out experiments using kites and balloons, becoming so accomplished that he and his brother set a world record in 1906 by flying for 52 hours in a balloon.

Wegener first conceived of continental drift in 1910 while examining a world map in an atlas, but it took 2 years for him to assemble sufficient data to propose the idea in public. He published the results in book form in 1915. Wegener's evidence went far beyond the congruence in the shapes of the continents. He proposed that the similarities between fossils found only in South America and Africa indicated that these two continents were joined at one time. He also showed that resemblances among living animal species on different continents could best be explained by assuming that the continents were once connected in a supercontinent he called *Pangaea* (from Greek elements meaning "all land").

Wegener's suggestion was met with a hostile reaction from most scientists. Although he had marshaled an impressive list of arguments for his hypothesis, he was missing a *mechanism*. No one could explain *how* solid continents could drift over thousands of miles. A few scientists were sufficiently impressed by Wegener's work to continue searching for additional evidence, but many found the notion of moving continents too revolutionary to take seriously. Developing an understanding of the mechanism (plate tectonics) would take decades of further progress in geology, oceanography, and geophysics.

Wegener was disappointed in the reception of his suggestion, but he continued his research and, in 1924, he was appointed to a special meteorology and geophysics professorship created especially for him at the University of Graz (where he was, however, ostracized by most of the geology faculty). Four years later, on his fourth expedition to his beloved Greenland, he celebrated his fiftieth birthday with colleagues and then set off on foot toward a different camp on the island. He never made it; he was found a few days later, dead of an apparent heart attack.

Critics of science often point to the resistance to the continental drift hypothesis as an example of the flawed way that scientists regard new ideas. (Many people who have advanced crackpot theories have claimed that they are being ridiculed unjustly, just as Wegener was.) But we think there is a more positive light in which to view the story of Wegener's suggestion. Scientists in

his day maintained a skeptical attitude because they needed more evidence and a clear mechanism that would fit what they understood about nature. Once the evidence and the mechanism were clear, Wegener's hypothesis quickly became the centerpiece of our view of a dynamic Earth.

Link to Learning

See how the drift of the continents has changed the appearance of our planet's crust.

Rift and Subduction Zones

Plates pull apart from each other along rift zones, such as the Mid-Atlantic ridge, driven by upwelling currents in the mantle (Figure 8.9). A few rift zones are found on land. The best known is the central African rift—an area where the African continent is slowly breaking apart. Most rift zones, however, are in the oceans. Molten rock rises from below to fill the space between the receding plates; this rock is basaltic lava, the kind of igneous rock that forms most of the ocean basins.

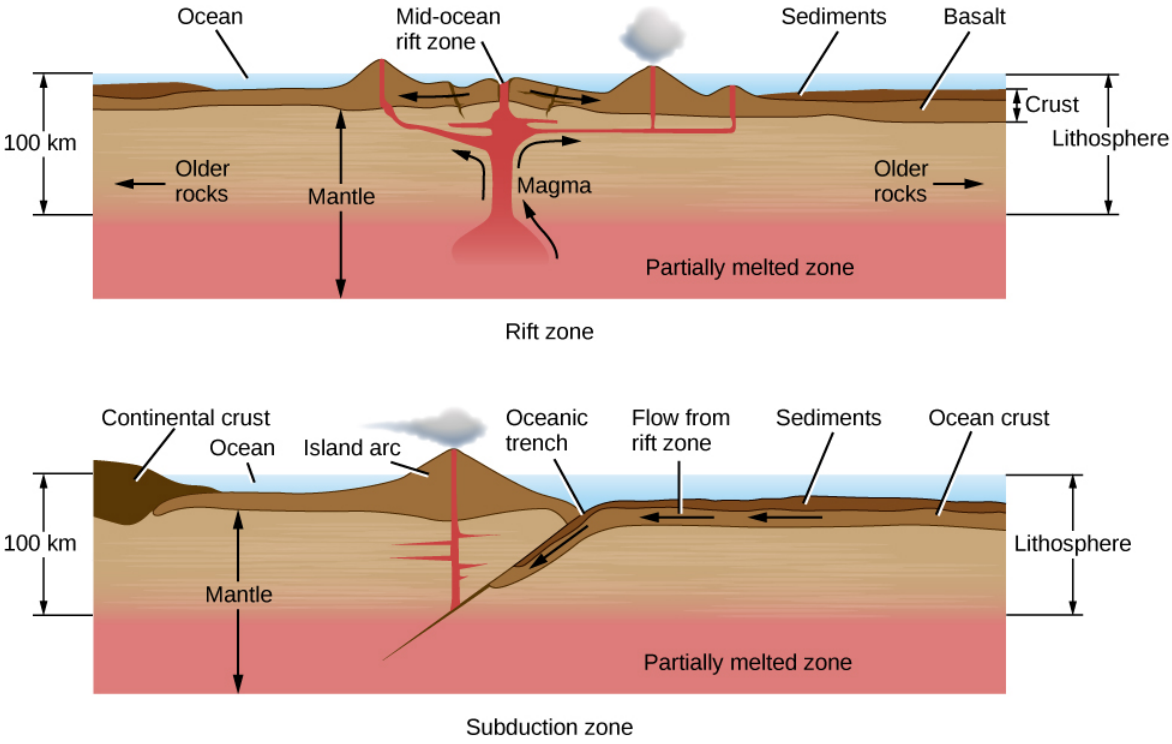


Figure 8.9 : Rift Zone and Subduction Zone. Rift and subduction zones are the regions (mostly beneath the oceans) where new crust is formed and old crust is destroyed as part of the cycle of plate tectonics.

From a knowledge of how the seafloor is spreading, we can calculate the average age of the oceanic crust. About 60,000 kilometers of active rifts have been identified, with average separation rates of about 5 centimeters per year. The new area added to Earth each year is about 2 square kilometers, enough to renew the entire oceanic crust in a little more than 100 million years. This is a very short interval in geological time—less than 3% of the age of Earth. The present ocean basins thus turn out to be among the youngest features on our planet.

As new crust is added to Earth, the old crust must go somewhere. When two plates come together, one plate is often forced beneath another in what is called a subduction zone (Figure 8.9). In general, the thick continental masses cannot be subducted, but the thinner oceanic plates can be rather readily thrust down into the upper mantle. Often a subduction zone is marked by an ocean trench; a fine example of this type of feature is the deep Japan trench along the coast of Asia. The subducted plate is forced down into regions of high pressure and temperature, eventually melting several hundred kilometers below the surface. Its material is recycled into a downward-flowing convection current, ultimately balancing the flow of material that rises along rift zones. The amount of crust destroyed at subduction zones is approximately equal to the amount formed at rift zones.

All along the subduction zone, earthquakes and volcanoes mark the death throes of the plate. Some of the most destructive earthquakes in history have taken place along subduction zones, including the 1923 Yokohama earthquake and fire that killed

100,000 people, the 2004 Sumatra earthquake and tsunami that killed more than 200,000 people, and the 2011 Tohoku earthquake that resulted in the meltdown of three nuclear power reactors in Japan.

Fault Zones and Mountain Building

Along much of their length, the crustal plates slide parallel to each other. These plate boundaries are marked by cracks or faults. Along active fault zones, the motion of one plate with respect to the other is several centimeters per year, about the same as the spreading rates along rifts.

One of the most famous faults is the San Andreas Fault in California, which lies at the boundary between the Pacific plate and the North American plate (Figure 8.10). This fault runs from the Gulf of California to the Pacific Ocean northwest of San Francisco. The Pacific plate, to the west, is moving northward, carrying Los Angeles, San Diego, and parts of the southern California coast with it. In several million years, Los Angeles may be an island off the coast of San Francisco.



Figure 8.10 : San Andreas Fault. We see part of a very active region in California where one crustal plate is sliding sideways with respect to the other. The fault is marked by the valley running up the right side of the photo. Major slippages along this fault can produce extremely destructive earthquakes. (credit: John Wiley)

Unfortunately for us, the motion along fault zones does not take place smoothly. The creeping motion of the plates against each other builds up stresses in the crust that are released in sudden, violent slippages that generate earthquakes. Because the average motion of the plates is constant, the longer the interval between earthquakes, the greater the stress and the more energy released when the surface finally moves.

For example, the part of the San Andreas Fault near the central California town of Parkfield has slipped every 25 years or so during the past century, moving an average of about 1 meter each time. In contrast, the average interval between major earthquakes in the Los Angeles region is about 150 years, and the average motion is about 7 meters. The last time the San Andreas fault slipped in this area was in 1857; tension has been building ever since, and sometime soon it is bound to be released. Sensitive instruments placed within the Los Angeles basin show that the basin is distorting and contracting in size as these tremendous pressures build up beneath the surface.

✔ Example 8.1: Fault Zones and Plate Motion

After scientists mapped the boundaries between tectonic plates in Earth's crust and measured the annual rate at which the plates move (which is about 5 cm/year), we could estimate quite a lot about the rate at which the geology of Earth is changing. As an example, let's suppose that the next slippage along the San Andreas Fault in southern California takes place in the year 2027 and that it completely relieves the accumulated strain in this region. How much slippage is required for this to occur?

Solution

The speed of motion of the Pacific plate relative to the North American plate is 5 cm/y. That's 500 cm (or 5 m) per century. The last southern California earthquake was in 1857. The time from 1857 to 2027 is

170 y, or 1.7 centuries, so the slippage to relieve the strain completely would be $5\text{m/century} \times 1.7\text{centuries} = 8.5\text{m}$.

? Exercise 7.3.1

If the next major southern California earthquake occurs in 2047 and only relieves one-half of the accumulated strain, how much slippage will occur?

Answer

The difference in time from 1857 to 2047 is 190 y, or 1.9 centuries. Because only half the strain is released, this is equivalent to half the annual rate of motion. The total slippage comes to $0.5 \times 5\text{m/century} \times 1.9\text{centuries} = 4.75\text{m}$.

When two continental masses are moving on a collision course, they push against each other under great pressure. Earth buckles and folds, dragging some rock deep below the surface and raising other folds to heights of many kilometers. This is the way many, but not all, of the mountain ranges on Earth were formed. The Alps, for example, are a result of the African plate bumping into the Eurasian plate. As we will see, however, quite different processes produced the mountains on other planets.

Once a mountain range is formed by upthrusting of the crust, its rocks are subject to erosion by water and ice. The sharp peaks and serrated edges have little to do with the forces that make the mountains initially. Instead, they result from the processes that tear down mountains. Ice is an especially effective sculptor of rock (Figure 8.11). In a world without moving ice or running water (such as the Moon or Mercury), mountains remain smooth and dull.



Figure 8.11 : Mountains on Earth. The Torres del Paine are a young region of Earth's crust where sharp mountain peaks are being sculpted by glaciers. We owe the beauty of our young, steep mountains to the erosion by ice and water. (credit: David Morrison)

Volcanoes

Volcanoes mark locations where lava rises to the surface. One example is mid ocean ridges, which are long undersea mountain ranges formed by lava rising from Earth's mantle at plate boundaries. A second major kind of volcanic activity is associated with subduction zones, and volcanoes sometimes also appear in regions where continental plates are colliding. In each case, the volcanic activity gives us a way to sample some of the material from deeper within our planet.

Other volcanic activity occurs above mantle "hot spots"—areas far from plate boundaries where heat is nevertheless rising from the interior of Earth. One of the best-known hot spots is under the island of Hawaii, where it currently supplies the heat to maintain three active volcanoes, two on land and one under the ocean. The Hawaii hot spot has been active for at least 100 million years. As Earth's plates have moved during that time, the hot spot has generated a 3500-kilometer-long chain of volcanic islands. The tallest Hawaiian volcanoes are among the largest individual mountains on Earth, more than 100 kilometers in diameter and rising 9 kilometers above the ocean floor. One of the Hawaiian volcanic mountains, the now-dormant Maunakea, has become one of the world's great sites for doing astronomy.

Link to Learning

The US Geological Service provides an interactive map of the famous “ring of fire,” which is the chain of volcanoes surrounding the Pacific Ocean, and shows the Hawaiian “hot spot” enclosed within.

Not all volcanic eruptions produce mountains. If lava flows rapidly from long cracks, it can spread out to form lava plains. The largest known terrestrial eruptions, such as those that produced the Snake River basalts in the northwestern United States or the Deccan plateau in India, are of this type. Similar lava plains are found on the Moon and the other terrestrial planets.

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7.4: Earth's Atmosphere

Learning Objectives

By the end of this section, you will be able to:

- Differentiate between Earth's various atmospheric layers
- Describe the chemical composition and possible origins of our atmosphere
- Explain the difference between weather and climate

We live at the bottom of the ocean of air that envelops our planet. The atmosphere, weighing down upon Earth's surface under the force of gravity, exerts a pressure at sea level that scientists define as 1 bar (a term that comes from the same root as *barometer*, an instrument used to measure atmospheric pressure). A bar of pressure means that each square centimeter of Earth's surface has a weight equivalent to 1.03 kilograms pressing down on it. Humans have evolved to live at this pressure; make the pressure a lot lower or higher and we do not function well.

The total mass of Earth's atmosphere is about 5×10^{18} kilograms. This sounds like a large number, but it is only about a millionth of the total mass of Earth. The atmosphere represents a smaller fraction of Earth than the fraction of your mass represented by the hair on your head.

Structure of the Atmosphere

The structure of the atmosphere is illustrated in Figure 8.12. Most of the atmosphere is concentrated near the surface of Earth, within about the bottom 10 kilometers where clouds form and airplanes fly. Within this region—called the troposphere—warm air, heated by the surface, rises and is replaced by descending currents of cooler air; this is an example of convection. This circulation generates clouds and wind. Within the troposphere, temperature decreases rapidly with increasing elevation to values near 50 °C below freezing at its upper boundary, where the stratosphere begins. Most of the stratosphere, which extends to about 50 kilometers above the surface, is cold and free of clouds.

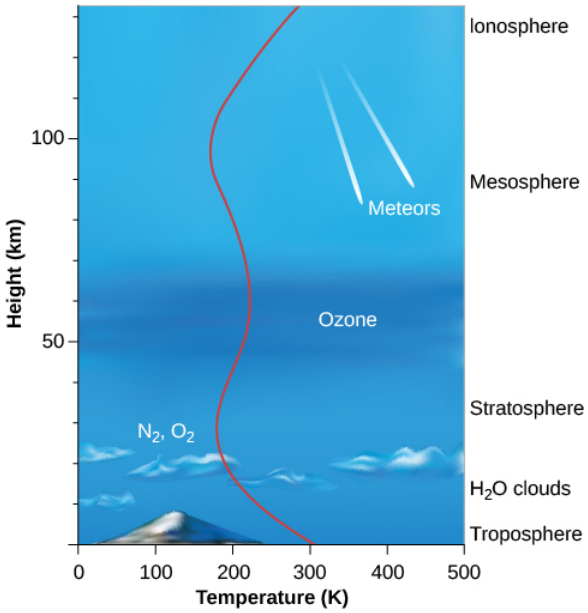


Figure 8.12 : Structure of Earth's Atmosphere. Height increases up the left side of the diagram, and the names of the different atmospheric layers are shown at the right. In the upper ionosphere, ultraviolet radiation from the Sun can strip electrons from their atoms, leaving the atmosphere ionized. The curving red line shows the temperature (see the scale on the *x*-axis).

Near the top of the stratosphere is a layer of ozone (O_3), a form of oxygen with three atoms per molecule instead of the usual two. Because ozone is a good absorber of ultraviolet light, it protects the surface from some of the Sun's dangerous ultraviolet radiation, making it possible for life to exist on Earth. The breakup of ozone adds heat to the stratosphere, reversing the decreasing temperature trend in the troposphere. Because ozone is essential to our survival, we reacted with justifiable concern to evidence that became clear in the 1980s that atmospheric ozone was being destroyed by human activities. By international agreement, the

production of industrial chemicals that cause ozone depletion, called chlorofluorocarbons, or CFCs, has been phased out. As a result, ozone loss has stopped and the “ozone hole” over the Antarctic is shrinking gradually. This is an example of how concerted international action can help maintain the habitability of Earth.

Link to Learning

Visit NASA’s scientific visualization studio for a short video of what would have happened to Earth’s ozone layer by 2065 if CFCs had not been regulated.

At heights above 100 kilometers, the atmosphere is so thin that orbiting satellites can pass through it with very little friction. Many of the atoms are ionized by the loss of an electron, and this region is often called the ionosphere. At these elevations, individual atoms can occasionally escape completely from the gravitational field of Earth. There is a continuous, slow leaking of atmosphere —especially of lightweight atoms, which move faster than heavy ones. Earth’s atmosphere cannot, for example, hold on for long to hydrogen or helium, which escape into space. Earth is not the only planet to experience atmosphere leakage. Atmospheric leakage also created Mars’ thin atmosphere. Venus’ dry atmosphere evolved because its proximity to the Sun vaporized and dissociated any water, with the component gases lost to space.

Atmospheric Composition and Origin

At Earth’s surface, the atmosphere consists of 78% nitrogen (N_2), 21% oxygen (O_2), and 1% argon (Ar), with traces of water vapor (H_2O), carbon dioxide (CO_2), and other gases. Variable amounts of dust particles and water droplets are also found suspended in the air.

A complete census of Earth’s volatile materials, however, should look at more than the gas that is now present. *Volatile* materials are those that evaporate at a relatively low temperature. If Earth were just a little bit warmer, some materials that are now liquid or solid might become part of the atmosphere. Suppose, for example, that our planet were heated to above the boiling point of water (100 °C, or 373 K); that’s a large change for humans, but a small change compared to the range of possible temperatures in the universe. At 100 °C, the oceans would boil and the resulting water vapor would become a part of the atmosphere.

To estimate how much water vapor would be released, note that there is enough water to cover the entire Earth to a depth of about 300 meters. Because the pressure exerted by 10 meters of water is equal to about 1 bar, the average pressure at the ocean floor is about 300 bars. Water weighs the same whether in liquid or vapor form, so if the oceans boiled away, the atmospheric pressure of the water would still be 300 bars. Water would therefore greatly dominate Earth’s atmosphere, with nitrogen and oxygen reduced to the status of trace constituents.

On a warmer Earth, another source of additional atmosphere would be found in the sedimentary carbonate rocks of the crust. These minerals contain abundant carbon dioxide. If all these rocks were heated, they would release about 70 bars of CO_2, far more than the current CO_2 pressure of only 0.0005 bar. Thus, the atmosphere of a warm Earth would be dominated by water vapor and carbon dioxide, with a surface pressure nearing 400 bars.

Several lines of evidence show that the composition of Earth’s atmosphere has changed over our planet’s history. Scientists can infer the amount of atmospheric oxygen, for example, by studying the chemistry of minerals that formed at various times. We examine this issue in more detail later in this chapter.

Today we see that CO_2, H_2O, sulfur dioxide (SO_2), and other gases are released from deeper within Earth through the action of volcanoes. (For CO_2, the primary source today is the burning of fossil fuels, which releases far more CO_2 than that from volcanic eruptions.) Much of this apparently new gas, however, is recycled material that has been subducted through plate tectonics. But where did our planet’s original atmosphere come from?

Three possibilities exist for the original source of Earth’s atmosphere and oceans: (1) the atmosphere could have been formed with the rest of Earth as it accumulated from debris left over from the formation of the Sun; (2) it could have been released from the interior through volcanic activity, subsequent to the formation of Earth; or (3) it may have been derived from impacts by comets and asteroids from the outer parts of the solar system. Current evidence favors a combination of the interior and impact sources.

Weather and Climate

All planets with atmospheres have *weather*, which is the name we give to the circulation of the atmosphere. The energy that powers the weather is derived primarily from the sunlight that heats the surface. Both the rotation of the planet and slower seasonal changes cause variations in the amount of sunlight striking different parts of Earth. The atmosphere and oceans redistribute the heat

from warmer to cooler areas. Weather on any planet represents the response of its atmosphere to changing inputs of energy from the Sun (see Figure 8.13 for a dramatic example).



Figure 8.13 : Storm from Space. This satellite image shows Hurricane Irene in 2011, shortly before the storm hit land in New York City. The combination of Earth's tilted axis of rotation, moderately rapid rotation, and oceans of liquid water can lead to violent weather on our planet. (credit: NASA/NOAA GOES Project)

Climate is a term used to refer to the effects of the atmosphere that last through decades and centuries. Changes in climate (as opposed to the random variations in weather from one year to the next) are often difficult to detect over short time periods, but as they accumulate, their effect can be devastating. One saying is that "Climate is what you expect, and weather is what you get." Modern farming is especially sensitive to temperature and rainfall; for example, calculations indicate that a drop of only 2 °C throughout the growing season would cut the wheat production by half in Canada and the United States. At the other extreme, an increase of 2 °C in the average temperature of Earth would be enough to melt many glaciers, including much of the ice cover of Greenland, raising sea level by as much as 10 meters, flooding many coastal cities and ports, and putting small islands completely under water.

The best documented changes in Earth's climate are the great ice ages, which have lowered the temperature of the Northern Hemisphere periodically over the past half million years or so (Figure 8.14). The last ice age, which ended about 14,000 years ago, lasted some 20,000 years. At its height, the ice was almost 2 kilometers thick over Boston and stretched as far south as New York City.

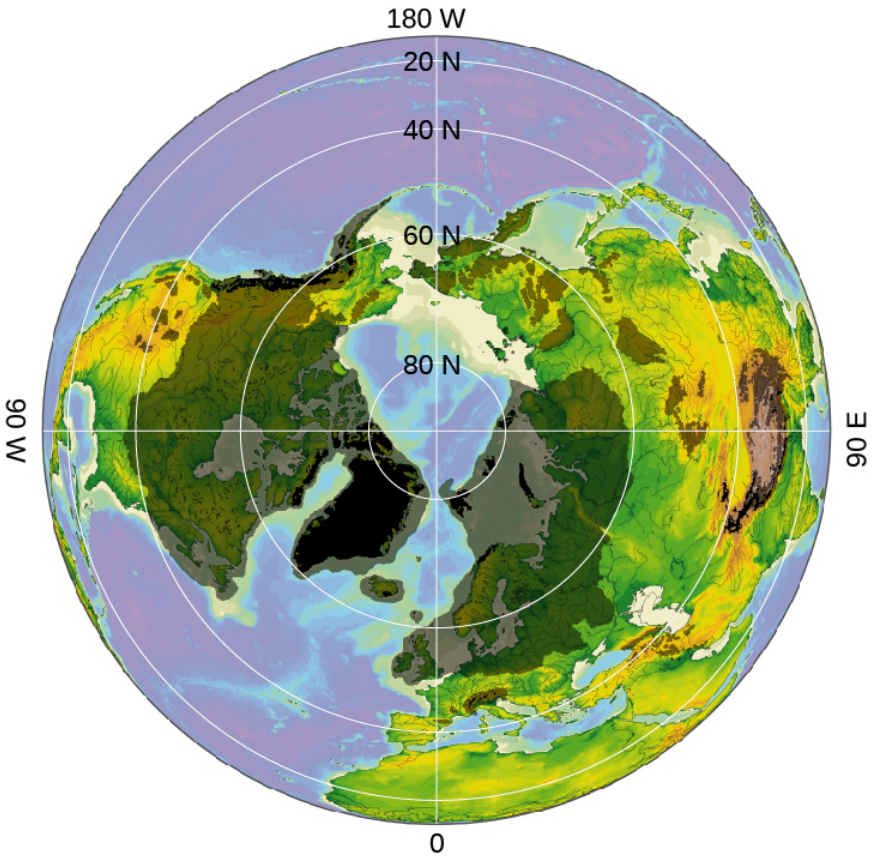


Figure 8.14 : Ice Age. This computer-generated image shows the frozen areas of the Northern Hemisphere during past ice ages from the vantage point of looking down on the North Pole. The area in black indicates the most recent glaciation (coverage by glaciers), and the area in gray shows the maximum level of glaciation ever reached. (credit: modification of work by Hannes Grobe/AWI)

These ice ages were primarily the result of changes in the tilt of Earth's rotational axis, produced by the gravitational effects of the other planets. We are less certain about evidence that at least once (and perhaps twice) about a billion years ago, the entire ocean froze over, a situation called *snowball Earth*.

The development and evolution of life on Earth has also produced changes in the composition and temperature of our planet's atmosphere, as we shall see in the next section.

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7.5: Life, Chemical Evolution, and Climate Change

Learning Objectives

By the end of this section, you will be able to:

- Outline the origins and subsequent diversity of life on Earth
- Explain the ways that life and geological activity have influenced the evolution of the atmosphere
- Describe the causes and effects of the atmospheric greenhouse effect and global warming
- Describe the impact of human activity on our planet's atmosphere and ecology

As far as we know, Earth seems to be the only planet in the solar system with life. The origin and development of life are an important part of our planet's story. Life arose early in Earth's history, and living organisms have been interacting with their environment for billions of years. We recognize that life-forms have evolved to adapt to the environment on Earth, and we are now beginning to realize that Earth itself has been changed in important ways by the presence of living matter. The study of the coevolution of life and our planet is one of the subjects of the modern science of *astrobiology*.

The Origin of Life

The record of the birth of life on Earth has been lost in the restless motions of the crust. According to chemical evidence, by the time the oldest surviving rocks were formed about 3.9 billion years ago, life already existed. At 3.5 billion years ago, life had achieved the sophistication to build large colonies called *stromatolites*, a form so successful that stromatolites still grow on Earth today (Figure 8.15). But, few rocks survive from these ancient times, and abundant fossils have been preserved only during the past 600 million years—less than 15% of our planet's history.



Figure 8.15 : Cross-Sections of Fossil Stromatolites. This polished cross-section of a fossilized colony of stromatolites dates to the Precambrian Era. The layered, domelike structures are mats of sediment trapped in shallow waters by large numbers of blue-green bacteria that can photosynthesize. Such colonies of microorganisms date back more than 3 billion years. (credit: James St. John)

There is little direct evidence about the actual origin of life. We know that the atmosphere of early Earth, unlike today's, contained abundant carbon dioxide and some methane, but no oxygen gas. In the absence of oxygen, many complex chemical reactions are possible that lead to the production of amino acids, proteins, and other chemical building blocks of life. Therefore, it seems likely that these chemical building blocks were available very early in Earth's history and they would have combined to make living organisms.

For tens of millions of years after Earth's formation, life (perhaps little more than large molecules, like the viruses of today) probably existed in warm, nutrient-rich seas, living off accumulated organic chemicals. When this easily accessible food became depleted, life began the long evolutionary road that led to the vast numbers of different organisms on Earth today. As it did so, life began to influence the chemical composition of the atmosphere.

In addition to the study of life's history as revealed by chemical and fossil evidence in ancient rocks, scientists use tools from the rapidly advancing fields of genetics and *genomics*—the study of the genetic code that is shared by all life on Earth. While each individual has a unique set of genes (which is why genetic "fingerprinting" is so useful for the study of crime), we also have many genetic traits in common. Your *genome*, the complete map of the DNA in your body, is identical at the 99.9% level to that of Julius Caesar or Marie Curie. At the 99% level, human and chimpanzee genomes are the same. By looking at the gene sequences of many

organisms, we can determine that all life on Earth is descended from a common ancestor, and we can use the genetic variations among species as a measure of how closely different species are related.

These genetic analysis tools have allowed scientists to construct what is called the “tree of life” (Figure 8.16). This diagram illustrates the way organisms are related by examining one sequence of the nucleic acid RNA that all species have in common. This figure shows that life on Earth is dominated by microscopic creatures that you have probably never heard of. Note that the plant and animal kingdoms are just two little branches at the far right. Most of the diversity of life, and most of our evolution, has taken place at the microbial level. Indeed, it may surprise you to know that there are more microbes in a bucket of soil than there are stars in the Galaxy. You may want to keep this in mind when, later in this book, we turn to the search for life on other worlds. The “aliens” that are most likely to be out there are microbes.

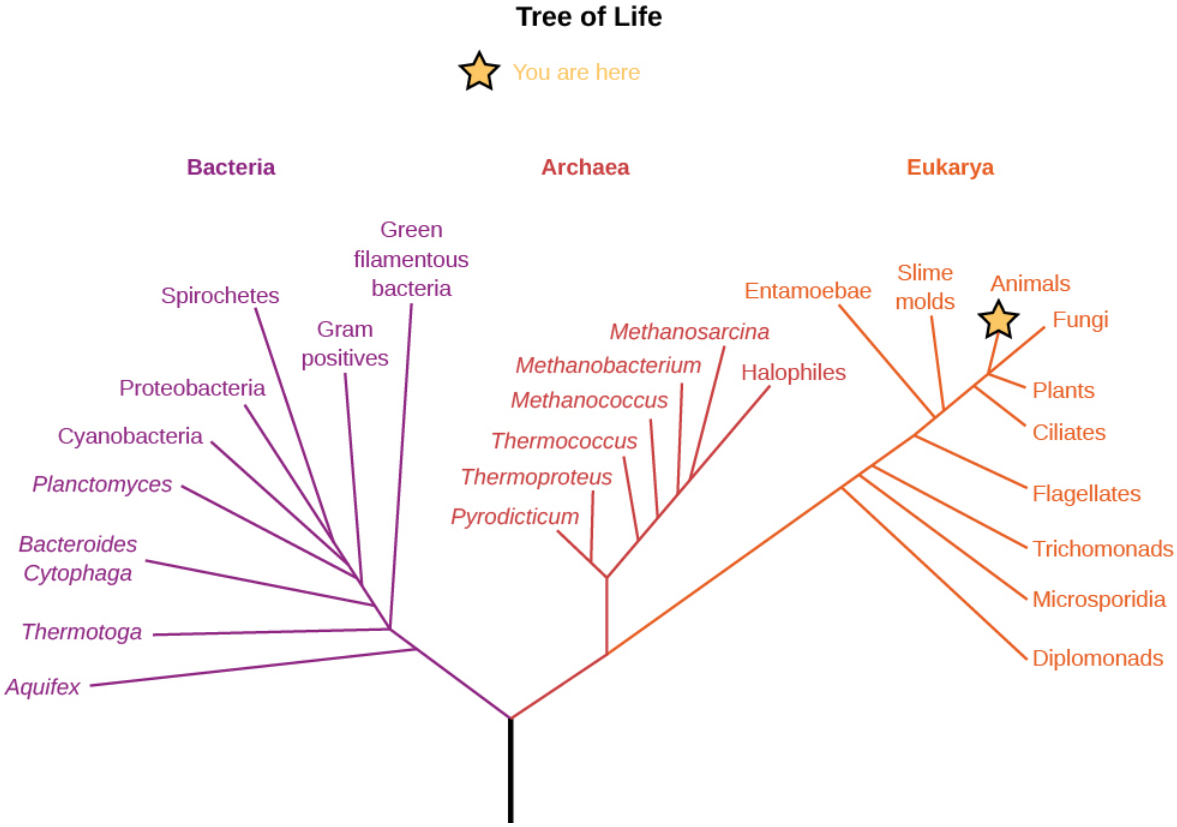


Figure 8.16 : Tree of Life. This chart shows the main subdivisions of life on Earth and how they are related. Note that the animal and plant kingdoms are just short branches on the far right, along with the fungi. The most fundamental division of Earth’s living things is onto three large domains called bacteria, archaea, and eukarya. Most of the species listed are microscopic. (credit: modification of work by Eric Gaba)

Such genetic studies lead to other interesting conclusions as well. For example, it appears that the earliest surviving terrestrial life-forms were all adapted to live at high temperatures. Some biologists think that life might actually have begun in locations on our planet that were extremely hot. Yet another intriguing possibility is that life began on Mars (which cooled sooner) rather than Earth and was “seeded” onto our planet by meteorites traveling from Mars to Earth. Mars rocks are still making their way to Earth, but so far none has shown evidence of serving as a “spaceship” to carry microorganisms from Mars to Earth.

The Evolution of the Atmosphere

One of the key steps in the evolution of life on Earth was the development of blue-green algae, a very successful life-form that takes in carbon dioxide from the environment and releases oxygen as a waste product. These successful microorganisms proliferated, giving rise to all the lifeforms we call plants. Since the energy for making new plant material from chemical building blocks comes from sunlight, we call the process photosynthesis.

Studies of the chemistry of ancient rocks show that Earth’s atmosphere lacked abundant free oxygen until about 2 billion years ago, despite the presence of plants releasing oxygen by photosynthesis. Apparently, chemical reactions with Earth’s crust removed the oxygen gas as quickly as it formed. Slowly, however, the increasing evolutionary sophistication of life led to a growth in the plant

population and thus increased oxygen production. At the same time, it appears that increased geological activity led to heavy erosion on our planet's surface. This buried much of the plant carbon before it could recombine with oxygen to form CO_2.

Free oxygen began accumulating in the atmosphere about 2 billion years ago, and the increased amount of this gas led to the formation of Earth's ozone layer (recall that ozone is a triple molecule of oxygen, O_3), which protects the surface from deadly solar ultraviolet light. Before that, it was unthinkable for life to venture outside the protective oceans, so the landmasses of Earth were barren.

The presence of oxygen, and hence ozone, thus allowed colonization of the land. It also made possible a tremendous proliferation of animals, which lived by taking in and using the organic materials produced by plants as their own energy source.

As animals evolved in an environment increasingly rich in oxygen, they were able to develop techniques for breathing oxygen directly from the atmosphere. We humans take it for granted that plenty of free oxygen is available in Earth's atmosphere, and we use it to release energy from the food we take in. Although it may seem funny to think of it this way, we are lifeforms that have evolved to breathe in the waste product of plants. It is plants and related microbes that are the primary producers, using sunlight to create energy-rich "food" for the rest of us.

On a planetary scale, one of the consequences of life has been a decrease in atmospheric carbon dioxide. In the absence of life, Earth would probably have an atmosphere dominated by CO_2, like Mars or Venus. But living things, in combination with high levels of geological activity, have effectively stripped our atmosphere of most of this gas.

The Greenhouse Effect and Global Warming

We have a special interest in the carbon dioxide content of the atmosphere because of the key role this gas plays in retaining heat from the Sun through a process called the greenhouse effect. To understand how the greenhouse effect works, consider the fate of sunlight that strikes the surface of Earth. The light penetrates our atmosphere, is absorbed by the ground, and heats the surface layers. At the temperature of Earth's surface, that energy is then reemitted as infrared or heat radiation (Figure 8.17). However, the molecules of our atmosphere, which allow visible light through, are good at absorbing infrared energy. As a result, CO_2 (along with methane and water vapor) acts like a blanket, trapping heat in the atmosphere and impeding its flow back to space. To maintain an energy balance, the temperature of the surface and lower atmosphere must increase until the total energy radiated by Earth to space equals the energy received from the Sun. The more CO_2 there is in our atmosphere, the higher the temperature at which Earth's surface reaches a new balance.

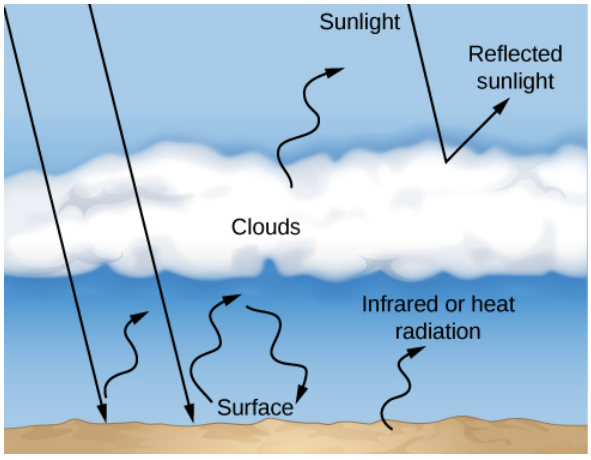


Figure 8.17 : How the Greenhouse Effect Works. Sunlight that penetrates to Earth's lower atmosphere and surface is reradiated as infrared or heat radiation, which is trapped by greenhouse gases such as water vapor, methane, and CO_2 in the atmosphere. The result is a higher surface temperature for our planet.

The greenhouse effect in a planetary atmosphere is similar to the heating of a gardener's greenhouse or the inside of a car left out in the Sun with the windows rolled up. In these examples, the window glass plays the role of greenhouse gases, letting sunlight in but reducing the outward flow of heat radiation. As a result, a greenhouse or car interior winds up much hotter than would be expected from the heating of sunlight alone. On Earth, the current greenhouse effect elevates the surface temperature by about 23 °C. Without this greenhouse effect, the average surface temperature would be well below freezing and Earth would be locked in a global ice age.

That’s the good news; the bad news is that the heating due to the greenhouse effect is increasing. Modern industrial society depends on energy extracted from burning fossil fuels. In effect, we are exploiting the energy-rich material created by photosynthesis tens of millions of years ago. As these ancient coal and oil deposits are oxidized (burned using oxygen), large quantities of carbon dioxide are released into the atmosphere. The problem is exacerbated by the widespread destruction of tropical forests, which we depend on to extract CO_2 from the atmosphere and replenish our supply of oxygen. In the past century of increased industrial and agricultural development, the amount of CO_2 in the atmosphere increased by about 30% and continues to rise at more than 0.5% per year.

Before the end of the present century, Earth’s CO_2 level is predicted to reach twice the value it had before the industrial revolution (Figure 8.18). The consequences of such an increase for Earth’s surface and atmosphere (and the creatures who live there) are likely to be complex changes in climate, and may be catastrophic for many species. Many groups of scientists are now studying the effects of such global warming with elaborate computer models, and climate change has emerged as the greatest known threat (barring nuclear war) to both industrial civilization and the ecology of our planet.

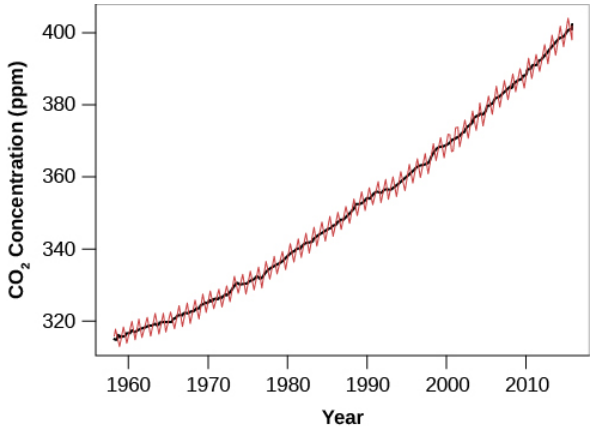


Figure 8.18 : Increase of Atmospheric Carbon Dioxide over Time. Scientists expect that the amount of CO_2 will double its preindustrial level before the end of the twenty-first century. Measurements of the isotopic signatures of this added CO_2 demonstrate that it is mostly coming from burning fossil fuels. (credit: modification of work by NOAA)

Link to Learning

This short PBS video explains the physics of the greenhouse effect.

Already climate change is widely apparent. Around the world, temperature records are constantly set and broken; all but one of the hottest recorded years have taken place since 2000. Glaciers are retreating, and the Arctic Sea ice is now much thinner than when it was first explored with nuclear submarines in the 1950s. Rising sea levels (from both melting glaciers and expansion of the water as its temperature rises) pose one of the most immediate threats, and many coastal cities have plans to build dikes or seawalls to hold back the expected flooding. The rate of temperature increase is without historical precedent, and we are rapidly entering “unknown territory” where human activities are leading to the highest temperatures on Earth in more than 50 million years.

Human Impacts on Our Planet

Earth is so large and has been here for so long that some people have trouble accepting that humans are really changing the planet, its atmosphere, and its climate. They are surprised to learn, for example, that the carbon dioxide released from burning fossil fuels is 100 times greater than that emitted by volcanoes. But, the data clearly tell the story that our climate is changing rapidly, and that almost all of the change is a result of human activity.

This is not the first time that humans have altered our environment dramatically. Some of the greatest changes were caused by our ancestors, before the development of modern industrial society. If aliens had visited Earth 50,000 years ago, they would have seen much of the planet supporting large animals of the sort that now survive only in Africa. The plains of Australia were occupied by giant marsupials such as diprotodon and zygomaturus (the size of our elephants today), and a species of kangaroo that stood 10 feet high. North America and North Asia hosted mammoths, saber tooth cats, mastodons, giant sloths, and even camels. The Islands of the Pacific teemed with large birds, and vast forests covered what are now the farms of Europe and China. Early human hunters killed many large mammals and marsupials, early farmers cut down most of the forests, and the Polynesian expansion across the Pacific doomed the population of large birds.

An even greater mass extinction is underway as a result of rapid climate change. In recognition of our impact on the environment, scientists have proposed giving a new name to the current epoch, the *anthropocene*, when human activity started to have a significant global impact. Although not an officially approved name, the concept of “anthropocene” is useful for recognizing that we humans now represent the dominant influence on our planet’s atmosphere and ecology, for better or for worse.

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7.6: Cosmic Influences on the Evolution of Earth

Learning Objectives

By the end of this section, you will be able to:

- Explain the scarcity of impact craters on Earth compared with other planets and moons
- Describe the evidence for recent impacts on Earth
- Detail how a massive impact changed the conditions for life on Earth, leading to the extinction of the dinosaurs
- Describe how impacts have influenced the evolution of life on Earth
- Discuss the search for objects that could potentially collide with our planet

In discussing Earth's geology earlier in this chapter, we dealt only with the effects of internal forces, expressed through the processes of plate tectonics and volcanism. On the Moon, in contrast, we see primarily craters, produced by the impacts of interplanetary debris such as asteroids and comets. Why don't we see more evidence on Earth of the kinds of impact craters that are so prominent on the Moon and other worlds?

Where Are the Craters on Earth?

It is not possible that Earth escaped being struck by the interplanetary debris that has pockmarked the Moon. From a cosmic perspective, the Moon is almost next door. Our atmosphere does make small pieces of cosmic debris burn up (which we see as *meteors*—commonly called shooting stars). But, the layers of our air provide no shield against the large impacts that form craters several kilometers in diameter and are common on the Moon.

In the course of its history, Earth must therefore have been impacted as heavily as the Moon. The difference is that, on Earth, these craters are destroyed by our active geology before they can accumulate. As plate tectonics constantly renews our crust, evidence of past cratering events is slowly erased. Only in the past few decades have geologists succeeded in identifying the eroded remnants of many impact craters (Figure 8.19). Even more recent is our realization that, over the history of Earth, these impacts have had an important influence on the evolution of life.

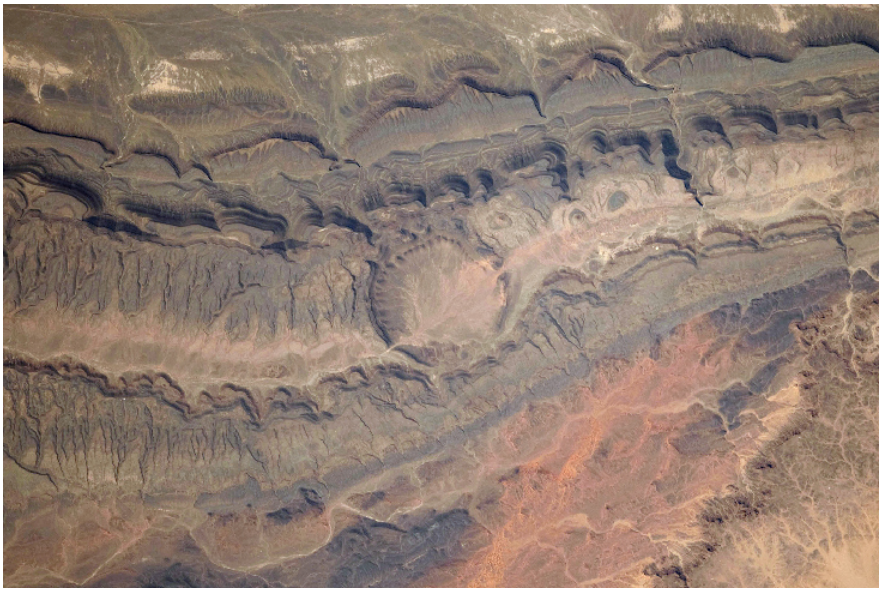


Figure 8.19 : Ouarkziz Impact Crater. Located in Algeria, this 4-km-wide crater (the round feature in the center) is the result of a meteor impact during the Cretaceous period. Although the crater has experienced heavy erosion, this image from the International Space Station shows the circular pattern resulting from impact. (credit: modification of work by NASA)

Recent Impacts

The collision of interplanetary debris with Earth is not a hypothetical idea. Evidence of relatively recent impacts can be found on our planet's surface. One well-studied historic collision took place on June 30, 1908, near the Tunguska River in Siberia. In this desolate region, there was a remarkable explosion in the atmosphere about 8 kilometers above the surface. The shock wave

flattened more than a thousand square kilometers of forest (Figure 8.20). Herds of reindeer and other animals were killed, and a man at a trading post 80 kilometers from the blast was thrown from his chair and knocked unconscious. The blast wave spread around the world, as recorded by instruments designed to measure changes in atmospheric pressure.



Figure 8.20 : Aftermath of the Tunguska Explosion. This photograph, taken 19 years after the blast, shows a part of the forest that was destroyed by the 5-megaton explosion, resulting when a stony projectile about the size of a small office building (40 meters in diameter) collided with our planet. (credit: modification of work by Leonid Kulik)

Despite this violence, no craters were formed by the Tunguska explosion. Shattered by atmospheric pressure, the stony projectile with a diameter of approximately 60 meters disintegrated above our planet's surface to create a blast equivalent to a 10-megaton nuclear bomb. Had it been smaller or more fragile, the impacting body would have dissipated its energy at high altitude and probably attracted no attention. Today, such high-altitude atmospheric explosions are monitored regularly by military surveillance systems.

If it had been larger or made of stronger material (such as metal), the Tunguska projectile would have penetrated all the way to the surface of Earth and exploded to form a crater. Instead, only the heat and shock of the atmospheric explosion reached the surface, but the devastation it left behind in Siberia bore witness to the power of such impacts. Imagine if the same rocky impactor had exploded over New York City in 1908; history books might today record it as one of the most deadly events in human history.

Tens of thousands of people witnessed directly the explosion of a smaller (20-meter) projectile over the Russian city of Chelyabinsk on an early winter morning in 2013. It exploded at a height of 21 kilometers in a burst of light brighter than the Sun, and the shockwave of the 0.5-megaton explosion broke tens of thousands of windows and sent hundreds of people to the hospital. Rock fragments (meteorites) were easily collected by people in the area after the blast because they landed on fresh snow.

Link to Learning

Dr. David Morrison, one of the original authors of this textbook, provides a nontechnical talk about the Chelyabinsk explosion, and impacts in general.

The best-known recent crater on Earth was formed about 50,000 years ago in Arizona. The projectile in this case was a lump of iron about 40 meters in diameter. Now called *Meteor Crater* and a major tourist attraction on the way to the Grand Canyon, the crater is about a mile across and has all the features associated with similar-size lunar impact craters (Figure 8.21). Meteor Crater is one of the few impact features on Earth that remains relatively intact; some older craters are so eroded that only a trained eye can distinguish them. Nevertheless, more than 150 have been identified. (See the list of suggested online sites at the end of this chapter if you want to find out more about these other impact scars.)



Figure 8.21 : Meteor Crater in Arizona. Here we see a 50,000-year-old impact crater made by the collision of a 40-meter lump of iron with our planet. Although impact craters are common on less active bodies such as the Moon, this is one of the very few well-preserved craters on Earth. (modification of work by D. Roddy/USGS)

Mass Extinction

The impact that produced Meteor Crater would have been dramatic indeed to any humans who witnessed it (from a safe distance) since the energy release was equivalent to a 10-megaton nuclear bomb. But such explosions are devastating only in their local areas; they have no *global* consequences. Much larger (and rarer) impacts, however, can disturb the ecological balance of the entire planet and thus influence the course of evolution.

The best-documented large impact took place 65 million years ago, at the end of what is now called the Cretaceous period of geological history. This time in the history of life on Earth was marked by a mass extinction, in which more than half of the species on our planet died out. There are a dozen or more mass extinctions in the geological record, but this particular event (nicknamed the “great dying”) has always intrigued paleontologists because it marks the end of the dinosaur age. For tens of millions of years these great creatures had flourished and dominated. Then, they suddenly disappeared (along with many other species), and thereafter mammals began the development and diversification that ultimately led to all of us.

The object that collided with Earth at the end of the Cretaceous period struck a shallow sea in what is now the Yucatán peninsula of Mexico. Its mass must have been more than a trillion tons, determined from study of a worldwide layer of sediment deposited from the dust cloud that enveloped the planet after its impact. First identified in 1979, this sediment layer is rich in the rare metal iridium and other elements that are relatively abundant in asteroids and comets, but exceedingly rare in Earth’s crust. Even though it was diluted by the material that the explosion excavated from the surface of Earth, this cosmic component can still be identified. In addition, this layer of sediment contains many minerals characteristic of the temperatures and pressures of a gigantic explosion.

The impact that led to the extinction of dinosaurs released energy equivalent to 5 billion Hiroshima-size nuclear bombs and excavated a crater 200 kilometers across and deep enough to penetrate through Earth’s crust. This large crater, named Chicxulub for a small town near its center, has subsequently been buried in sediment, but its outlines can still be identified (Figure 8.22). The explosion that created the Chicxulub crater lifted about 100 trillion tons of dust into the atmosphere. We can determine this amount by measuring the thickness of the sediment layer that formed when this dust settled to the surface.



Figure 8.22 : Site of the Chicxulub Crater. This map shows the location of the impact crater created 65 million years ago on Mexico's Yucatán peninsula. The crater is now buried under more than 500 meters of sediment. (credit: modification of work by "Carport"/Wikimedia)

Such a quantity of airborne material would have blocked sunlight completely, plunging Earth into a period of cold and darkness that lasted several months. Many plants dependent on sunlight would have died, leaving plant-eating animals without a food supply. Other worldwide effects included large-scale fires (started by the hot, flying debris from the explosion) that destroyed much of the planet's forests and grasslands, and a long period in which rainwater around the globe was acidic. It was these environmental effects, rather than the explosion itself, that were responsible for the mass extinction, including the demise of the dinosaurs.

Impacts and the Evolution of Life

It is becoming clear that many—perhaps most—mass extinctions in Earth's long history resulted from a variety of other causes, but in the case of the dinosaur killer, the cosmic impact certainly played a critical role and may have been the "final straw" in a series of climactic disturbances that resulted in the "great dying."

A catastrophe for one group of living things, however, may create opportunities for another group. Following each mass extinction, there is a sudden evolutionary burst as new species develop to fill the ecological niches opened by the event. Sixty-five million years ago, our ancestors, the mammals, began to thrive when so many other species died out. We are the lucky beneficiaries of this process.

Impacts by comets and asteroids represent the only mechanisms we know of that could cause truly global catastrophes and seriously influence the evolution of life all over the planet. As paleontologist Stephen Jay Gould of Harvard noted, such a perspective changes fundamentally our view of biological evolution. The central issues for the survival of a species must now include more than just its success in competing with other species and adapting to slowly changing environments, as envisioned by Darwin's idea of natural selection. Also required is an ability to survive random global catastrophes due to impacts.

Still earlier in its history, Earth was subject to even larger impacts from the leftover debris of planet formation. We know that the Moon was struck repeatedly by objects larger than 100 kilometers in diameter—1000 times more massive than the object that wiped out most terrestrial life 65 million years ago. Earth must have experienced similar large impacts during its first 700 million years of existence. Some of them were probably violent enough to strip the planet of most its atmosphere and to boil away its oceans. Such events would sterilize the planet, destroying any life that had begun. Life may have formed and been wiped out several times before our own microbial ancestors took hold sometime about 4 billion years ago.

The fact that the oldest surviving microbes on Earth are thermophiles (adapted to very high temperatures) can also be explained by such large impacts. An impact that was just a bit too small to sterilize the planet would still have destroyed anything that lived in what we consider “normal” environments, and only the creatures adapted to high temperatures would survive. Thus, the oldest surviving terrestrial lifeforms are probably the remnants of a sort of evolutionary bottleneck caused by repeated large impacts early in the planet’s history.

Impacts in Our Future?

The impacts by asteroids and comets that have had such a major influence on life are not necessarily a thing of the past. In the full scope of planetary history, 65 million years ago was just yesterday. Earth actually orbits the Sun within a sort of cosmic shooting gallery, and although major impacts are rare, they are by no means over. Humanity could suffer the same fate as the dinosaurs, or lose a city to the much more frequent impacts like the one over Tunguska, unless we figure out a way to predict the next big impact and to protect our planet. The fact that our solar system is home to some very large planets in outer orbits may be beneficial to us; the gravitational fields of those planets can be very effective at pulling in cosmic debris and shielding us from larger, more frequent impacts.

Beginning in the 1990s, a few astronomers began to analyze the cosmic impact hazard and to persuade the government to support a search for potentially hazardous asteroids. Several small but sophisticated wide-field telescopes are now used for this search, which is called the NASA Spaceguard Survey. Already we know that there are currently no asteroids on a collision course with Earth that are as big (10–15 kilometers) as the one that killed the dinosaurs. The Spaceguard Survey now concentrates on finding smaller potential impactors. By 2021, the search had netted more than 98 percent of the hazardous near-Earth asteroids larger than 1 kilometer. The Spaceguard Survey will soon be augmented by the Vera Rubin Telescope that will scan the full sky on a regular basis, and an orbiting search telescope is under development by NASA. Of course, we cannot make a similar statement about the asteroids that have not yet been discovered, but these will be found and evaluated one by one for their potential hazard. These asteroid surveys are one of the few really life-and-death projects carried out by astronomers, with a potential to help to save our planet from future major impacts. Scientists are now studying how we could protect ourselves from an impact if a large asteroid were discovered on a collision course. The NASA spacecraft called DART (Double Asteroid Redirection Test), launched in late 2021, will demonstrate one example of such technology by crashing into the small asteroid Diomorphos to slightly alter its orbit.

Link to Learning

The Torino Impact Hazard Scale is a method for categorizing the impact hazard associated with near-Earth objects such as asteroids and comets. It is a communication tool for astronomers and the public to assess the seriousness of collision predictions by combining probability statistics and known kinetic damage potentials into a single threat value.

Purdue University’s “Impact: Earth” calculator lets you input the characteristics of an approaching asteroid to determine the effect of its impact on our planet.

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7.7: Key Terms

bar
a force of 100,000 Newtons acting on a surface area of 1 square meter; the average pressure of Earth's atmosphere at sea level is 1.013 bars

basalt
igneous rock produced by the cooling of lava; makes up most of Earth's oceanic crust and is found on other planets that have experienced extensive volcanic activity

convection
movement caused within a gas or liquid by the tendency of hotter, and therefore less dense material, to rise and colder, denser material to sink under the influence of gravity, which consequently results in transfer of heat

core
the central part of the planet; consists of higher density material

crust
the outer layer of a terrestrial planet

fault
in geology, a crack or break in the crust of a planet along which slippage or movement can take place, accompanied by seismic activity

granite
a type of igneous silicate rock that makes up most of Earth's continental crust

greenhouse effect
the blanketing (absorption) of infrared radiation near the surface of a planet—for example, by CO_2 in its atmosphere

greenhouse gas
a gas in an atmosphere that absorbs and emits radiation within the thermal infrared range; on Earth, these atmospheric gases primarily include carbon dioxide, methane, and water vapor

igneous rock
rock produced by cooling from a molten state

magnetosphere
the region around a planet in which its intrinsic magnetic field dominates the interplanetary field carried by the solar wind; hence, the region within which charged particles can be trapped by the planetary magnetic field

mantle
the largest part of Earth's interior; lies between the crust and the core

mass extinction
the sudden disappearance in the fossil record of a large number of species of life, to be replaced by fossils of new species in subsequent layers; mass extinctions are indicators of catastrophic changes in the environment, such as might be produced by a large impact on Earth

metamorphic rock
rock produced by physical and chemical alteration (without melting) under high temperature and pressure

ozone
(O_3) a heavy molecule of oxygen that contains three atoms rather than the more normal two

photosynthesis
a complex sequence of chemical reactions through which some living things can use sunlight to manufacture products that store energy (such as carbohydrates), releasing oxygen as one by-product

plate tectonics
the motion of segments or plates of the outer layer of a planet over the underlying mantle

primitive rock
rock that has not experienced great heat or pressure and therefore remains representative of the original condensed materials from the solar nebula

rift zone
in geology, a place where the crust is being torn apart by internal forces generally associated with the injection of new material from the mantle and with the slow separation of tectonic plates

sedimentary rock
rock formed by the deposition and cementing of fine grains of material, such as pieces of igneous rock or the shells of living things

seismic wave
a vibration that travels through the interior of Earth or any other object; on Earth, these are generally caused by earthquakes

stratosphere
the layer of Earth’s atmosphere above the troposphere and below the ionosphere

subduction
the sideways and downward movement of the edge of a plate of Earth’s crust into the mantle beneath another plate

troposphere
the lowest level of Earth’s atmosphere, where most weather takes place

volcano
a place where material from a planet’s mantle erupts on its surface

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7.8: Summary

8.1 The Global Perspective

Earth is the prototype terrestrial planet. Its interior composition and structure are probed using seismic waves. Such studies reveal that Earth has a metal core and a silicate mantle. The outer layer, or crust, consists primarily of oceanic basalt and continental granite. A global magnetic field, generated in the core, produces Earth's magnetosphere, which can trap charged atomic particles.

8.2 Earth's Crust

Terrestrial rocks can be classified as igneous, sedimentary, or metamorphic. A fourth type, primitive rock, is not found on Earth. Our planet's geology is dominated by plate tectonics, in which crustal plates move slowly in response to mantle convection. The surface expression of plate tectonics includes continental drift, recycling of the ocean floor, mountain building, rift zones, subduction zones, faults, earthquakes, and volcanic eruptions of lava from the interior.

8.3 Earth's Atmosphere

The atmosphere has a surface pressure of 1 bar and is composed primarily of N_2 and O_2, plus such important trace gases as H_2O, CO_2, and O_3. Its structure consists of the troposphere, stratosphere, mesosphere, and ionosphere. Changing the composition of the atmosphere also influences the temperature. Atmospheric circulation (weather) is driven by seasonally changing deposition of sunlight. Many longer term climate variations, such as the ice ages, are related to changes in the planet's orbit and axial tilt.

8.4 Life, Chemical Evolution, and Climate Change

Life originated on Earth at a time when the atmosphere lacked O_2 and consisted mostly of CO_2. Later, photosynthesis gave rise to free oxygen and ozone. Modern genomic analysis lets us see how the wide diversity of species on the planet are related to each other. CO_2 and methane in the atmosphere heat the surface through the greenhouse effect. Increasing amounts of atmospheric CO_2 from burning of fossils fuels and release of frozen methane are causing the global warming of our planet.

8.5 Cosmic Influences on the Evolution of Earth

Earth, like the Moon and other planets, has been influenced by the impacts of cosmic debris, including such recent examples as Meteor Crater and the Tunguska explosion. Larger past impacts are implicated in some mass extinctions, including the large impact 65 million years ago at the end of the Cretaceous period that wiped out the dinosaurs and many other species. Today, astronomers are working to predict the next impact in advance, while other scientists are coming to grips with the effect of impacts on the evolution and diversity of life on Earth.

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7.9: For Further Exploration

Articles

Earth

Collins, W., et al. “The Physical Science behind Climate Change.” *Scientific American* (August 2007): 64. Why scientists are now confident that human activities are changing our planet’s climate.

Glatzmaier, G., & Olson, P. “Probing the Geodynamo.” *Scientific American* (April 2005): 50. Experiments and modeling that tell us about the source and reversals of Earth’s magnetic field.

Gurnis, M. “Sculpting the Earth from Inside Out.” *Scientific American* (March 2001): 40. On motions that lift and lower the continents.

Hartmann, W. “Piecing Together Earth’s Early History.” *Astronomy* (June 1989): 24.

Jewitt, D., & Young, E. “Oceans from the Skies.” *Scientific American* (March 2015): 36. How did Earth get its water after its initial hot period?

Impacts

Boslaugh, M. “In Search of Death-Plunge Asteroids.” *Astronomy (*July 2015): 28. On existing and proposed programs to search for earth-crossing asteroids.

Brusatte, S. “What Killed the Dinosaurs?” *Scientific American* (December 2015): 54. The asteroid hit Earth at an already vulnerable time.

Chyba, C. “Death from the Sky: Tunguska.” *Astronomy* (December 1993): 38. Excellent review article.

Durda, D. “The Chelyabinsk Super-Meteor.” *Sky & Telescope* (June 2013): 24. A nice summary with photos and eyewitness reporting.

Gasperini, L., et al. “The Tunguska Mystery.” *Scientific American* (June 2008): 80. A more detailed exploration of the site of the 1908 impact over Siberia.

Kring, D. “Blast from the Past.” *Astronomy* (August 2006): 46. Six-page introduction to Arizona’s meteor crater.

Websites

Earth

Astronaut Photography of Earth from Space: https://eol.jsc.nasa.gov/. A site with many images and good information.

Exploration of the Earth’s Magnetosphere: http://phy6.org/Education/Intro.html. An educational website by Dr. Daniel Stern.

NASA Goddard: Earth from Space: Fifteen Amazing Things in 15 Years: https://www.nasa.gov/content/goddard/earth-from-space-15-amazing-things-in-15-years. Images and videos that reveal things about our planet and its atmosphere.

U.S. Geological Survey: Earthquake Information Center: http://earthquake.usgs.gov/learn/

Views of the Solar System: http://www.solarviews.com/eng/earth.htm. Overview of Earth.

Impacts

B612 Foundation : https://b612foundation.org/. Set up by several astronauts for research and education about the asteroid threat to Earth and to build a telescope in space to search for dangerous asteroids.

Lunar and Planetary Institute: Introduction to Terrestrial Impact Craters: www.lpi.usra.edu/publications/slidesets/craters/. Includes images.

Meteor Crater Tourist Site: http://meteorcrater.com/.

NASA/Jet Propulsion Lab Near Earth Object Program: http://neo.jpl.nasa.gov/neo/.

What Are Near-Earth-Objects: http://spaceguardcentre.com/what-are-neos/. From the British Spaceguard Centre.

Videos

Earth

All Alone in the Night: http://apod.nasa.gov/apod/ap120305.html. Flying over Earth at night (2:30).

Earth: The Operator's Manual: earththeoperatorsmanual.com/feature-video/earth-the-operators-manual. A National Science Foundation–sponsored miniseries on climate change and energy, with geologist Richard Alley (53:43).

PBS NOVA Videos about Earth: http://www.pbs.org/wgbh/nova/earth/. Programs and information about planet Earth. Click full episodes on the menu at left to be taken to a nice array of videos.

U. S. National Weather Service: http://earth.nullschool.net. Real Time Globe of Earth showing wind patterns which can be zoomed and moved to your preferred view.

Impacts

Chelyabinsk Meteor: Can We Survive a Bigger Impact?: https://www.youtube.com/watch?v=Y-e6xyUZLLs. Talk by Dr. David Morrison (1:34:48).

Large Asteroid Impact Simulation: https://www.youtube.com/watch?v=bU1QPtOZQZU. Large asteroid impact simulation from the Discovery Channel (4:45).

Meteor Hits Russia February 15, 2013: https://www.youtube.com/watch?v=dpmXyJrs7iU. Archive of eyewitness footage (10:11).

Sentinel Mission: Finding an Asteroid Headed for Earth: https://www.youtube.com/watch?v=efz8c3ijD_A. Public lecture by astronaut Ed Lu (1:08:57).

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7.10: Collaborative Group Activities

A. If we can predict that lots of ground movement takes place along subduction zones and faults, then why do so many people live there? Should we try to do anything to discourage people from living in these areas? What inducement would your group offer people to move? Who would pay for the relocation? (Note that two of the original authors of this book live quite close to the San Andreas and Hayward faults. If they wrote this chapter and haven't moved, what are the chances others living in these kinds of areas will move?)

B. After your group reads the feature box on Alfred Wegener: Catching the Drift of Plate Tectonics, discuss some reasons his idea did not catch on right away among scientists. From your studies in this course and in other science courses (in college and before), can you cite other scientific ideas that we now accept but that had controversial beginnings? Can you think of any scientific theories that are still controversial today? If your group comes up with some, discuss ways scientists could decide whether each theory on your list is right.

C. Suppose we knew that a large chunk of rock or ice (about the same size as the one that hit 65 million years ago) will impact Earth in about 5 years. What could or should we do about it? (The film *Deep Impact* dealt with this theme.) Does your group think that the world as a whole should spend more money to find and predict the orbits of cosmic debris near Earth?

D. Carl Sagan pointed out that any defensive weapon that we might come up with to deflect an asteroid *away* from Earth could be used as an offensive weapon by an unstable dictator in the future to cause an asteroid not heading our way to come toward Earth. The history of human behavior, he noted, has shown that most weapons that are built (even with the best of motives) seem to wind up being used. Bearing this in mind, does your group think we should be building weapons to protect Earth from asteroid or comet impact? Can we afford not to build them? How can we safeguard against these collisions?

E. Is there evidence of climate change in your area over the past century? How would you distinguish a true climate change from the random variations in weather that take place from one year to the next?

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CHAPTER OVERVIEW

7.11: Exercises

7.11.1: Review Questions

7.11.2: Thought Questions

7.11.3: Figuring for Yourself

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7.11.1: Review Questions

Review Questions

1.

What is the thickest interior layer of Earth? The thinnest?

2.

What are Earth’s core and mantle made of? Explain how we know.

3.

Describe the differences among primitive, igneous, sedimentary, and metamorphic rock, and relate these differences to their origins.

4.

Explain briefly how the following phenomena happen on Earth, relating your answers to the theory of plate tectonics

A. earthquakes
B. continental drift
C. mountain building
D. volcanic eruptions
E. creation of the Hawaiian island chain

5.

What is the source of Earth’s magnetic field?

6.

Why is the shape of the magnetosphere not spherical like the shape of Earth?

7.

Although he did not present a mechanism, what were the key points of Alfred Wegener’s proposal for the concept of continental drift?

8.

List the possible interactions between Earth’s crustal plates that can occur at their boundaries.

9.

List, in order of decreasing altitude, the principle layers of Earth’s atmosphere.

10.

In which atmospheric layer are almost all water-based clouds formed?

11.

What is, by far, the most abundant component of Earth’s atmosphere?

12.

In which domain of living things do you find humankind?

13.

Describe three ways in which the presence of life has affected the composition of Earth’s atmosphere.

14.

Briefly describe the greenhouse effect.

15.

How do impacts by comets and asteroids influence Earth’s geology, its atmosphere, and the evolution of life?

16.

Why are there so many impact craters on our neighbor world, the Moon, and so few on Earth?

17.

Detail some of the anthropogenic changes to Earth’s climate and their potential impact on life.

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7.11.2: Thought Questions

Thought Questions

18.

If you wanted to live where the chances of a destructive earthquake were small, would you pick a location near a fault zone, near a mid ocean ridge, near a subduction zone, or on a volcanic island such as Hawaii? What are the relative risks of earthquakes at each of these locations?

19.

Which type of object would likely cause more damage if it struck near an urban area: a small metallic object or a large stony/icy one?

20.

If all life were destroyed on Earth by a large impact, would new life eventually form to take its place? Explain how conditions would have to change for life to start again on our planet.

21.

Why is a decrease in Earth's ozone harmful to life?

22.

Why are we concerned about the increases in CO_2 and other gases that cause the greenhouse effect in Earth's atmosphere? What steps can we take in the future to reduce the levels of CO_2 in our atmosphere? What factors stand in the way of taking the steps you suggest? (You may include technological, economic, and political factors in your answer.)

23.

Do you think scientists should make plans to defend Earth from future asteroid impacts? Is it right to intervene in the same evolutionary process that made the development of mammals (including us) possible after the big impact 65 million years ago?

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7.11.3: Figuring for Yourself

Figuring for Yourself

24.

Europe and North America are moving apart by about 5 m per century. As the continents separate, new ocean floor is created along the mid-Atlantic Rift. If the rift is 5000 km long, what is the total area of new ocean floor created in the Atlantic each century? (Remember that 1 km = 1000 m.)

25.

Over the entire Earth, there are 60,000 km of active rift zones, with average separation rates of 5 m/century. How much area of new ocean crust is created each year over the entire planet? (This area is approximately equal to the amount of ocean crust that is subducted since the total area of the oceans remains about the same.)

26.

With the information from Exercise 8.25, you can calculate the average age of the ocean floor. First, find the total area of the ocean floor (equal to about 60% of the surface area of Earth). Then compare this with the area created (or destroyed) each year. The average lifetime is the ratio of these numbers: the total area of ocean crust compared to the amount created (or destroyed) each year.

27.

What is the volume of new oceanic basalt added to Earth's crust each year? Assume that the thickness of the new crust is 5 km, that there are 60,000 km of rifts, and that the average speed of plate motion is
4 cm/y. What fraction of Earth's entire volume does this annual addition of new material represent?

28.

Suppose a major impact that produces a mass extinction takes place on Earth once every 5 million years. Suppose further that if such an event occurred today, you and most other humans would be killed (this would be true even if the human species as a whole survived). Such impact events are random, and one could take place at any time. Calculate the probability that such an impact will occur within the next 50 years (within your lifetime).

29.

How do the risks of dying from the impact of an asteroid or comet compare with other risks we are concerned about, such as dying in a car accident or from heart disease or some other natural cause? (Hint: To find the annual risk, go to the library or internet and look up the annual number of deaths from a particular cause in a particular country, and then divide by the population of that country.)

30.

What fraction of Earth's volume is taken up by the core?

31.

Approximately what percentage of Earth's radius is represented by the crust?

32.

What is the drift rate of the Pacific plate over the Hawaiian hot spot?

33.

What is the percent increase of atmospheric CO_2 in the past 20 years?

34.

Estimate the mass of the object that formed Meteor Crater in Arizona.

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CHAPTER OVERVIEW

8: The Moon

The Moon is the only other world human beings have ever visited. What is it like to stand on the surface of our natural satellite? And what can we learn from going there and bringing home pieces of a different world?

We begin our discussion of the planets as cratered worlds with two relatively simple objects: the Moon and Mercury. Unlike Earth, the Moon is geologically dead, a place that has exhausted its internal energy sources. Because its airless surface preserves events that happened long ago, the Moon provides a window on earlier epochs of solar system history. The planet Mercury is in many ways similar to the Moon, which is why the two are discussed together: both are relatively small, lacking in atmospheres, deficient in geological activity, and dominated by the effects of impact cratering. Still, the processes that have molded their surfaces are not unique to these two worlds. We shall see that they have acted on many other members of the planetary system as well.

8.1: Thinking Ahead
8.2: General Properties of the Moon
8.3: The Lunar Surface
8.4: Impact Craters
8.5: The Origin of the Moon
8.6: Key Terms
8.7: Summary
8.8: For Further Exploration
8.9: Collaborative Group Activities
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8.1: Thinking Ahead

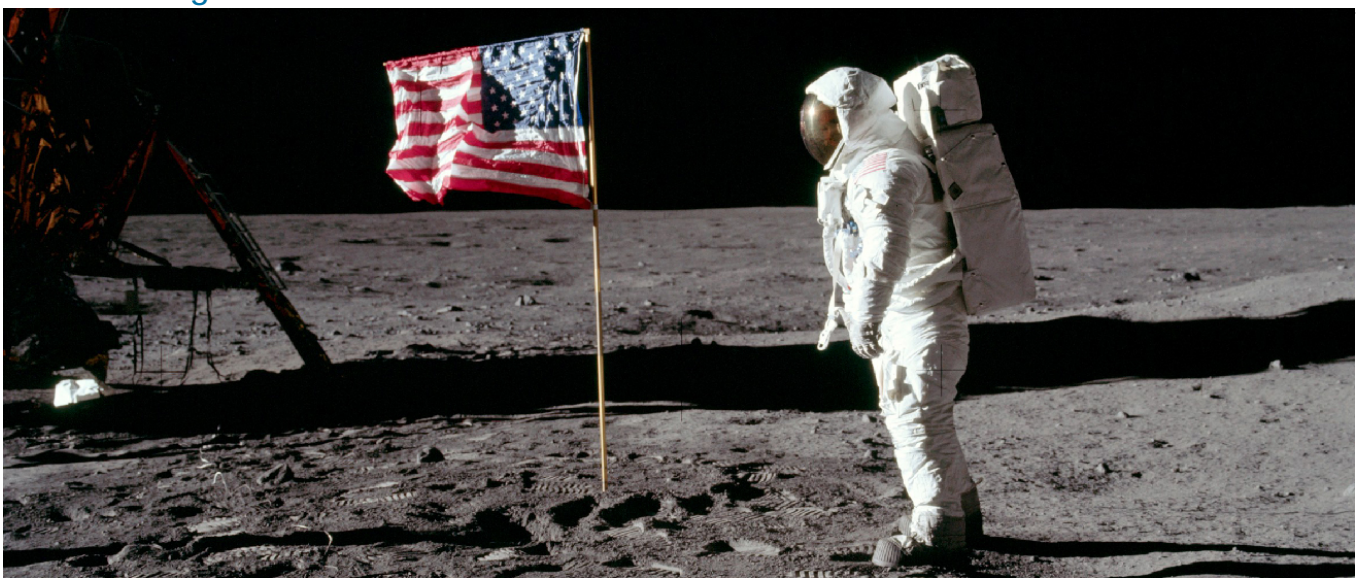


Figure 9.1 : Apollo 11 Astronaut Edwin “Buzz” Aldrin on the Surface of the Moon. Because there is no atmosphere, ocean, or geological activity on the Moon today, the footprints you see in the image will likely be preserved in the lunar soil for millions of years. The flag, by the way, was printed on a kind of foil which crinkled easily. That’s why it looks like it’s waving; there is no atmosphere on the Moon and, thus, no wind that can make a flag flutter. (credit: modification of work by NASA/ Neil A. Armstrong)

The Moon is the only other world human beings have ever visited. What is it like to stand on the surface of our natural satellite? And what can we learn from going there and bringing home pieces of a different world?

We begin our discussion of the planets as cratered worlds with two relatively simple objects: the Moon and Mercury. Unlike Earth, the Moon is geologically dead, a place that has exhausted its internal energy sources. Because its airless surface preserves events that happened long ago, the Moon provides a window on earlier epochs of solar system history. The planet Mercury is in many ways similar to the Moon, which is why the two are discussed together: both are relatively small, lacking in atmospheres, deficient in geological activity, and dominated by the effects of impact cratering. Still, the processes that have molded their surfaces are not unique to these two worlds. We shall see that they have acted on many other members of the planetary system as well.

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8.2: General Properties of the Moon

Learning Objectives

By the end of this section, you will be able to:

- Discuss what has been learned from both manned and robotic lunar exploration
- Describe the composition and structure of the Moon

The Moon has only one-eightieth the mass of Earth and about one-sixth Earth's surface gravity—too low to retain an atmosphere (Figure 9.2). Moving molecules of a gas can escape from a planet just the way a rocket does, and the lower the gravity, the easier it is for the gas to leak away into space. While the Moon can acquire a temporary atmosphere from impacting comets, this atmosphere is quickly lost by freezing onto the surface or by escape to surrounding space. The Moon today is dramatically deficient in a wide range of *volatiles*, those elements and compounds that evaporate at relatively low temperatures. Some of the Moon's properties are summarized in Table 9.1, along with comparative values for Mercury.

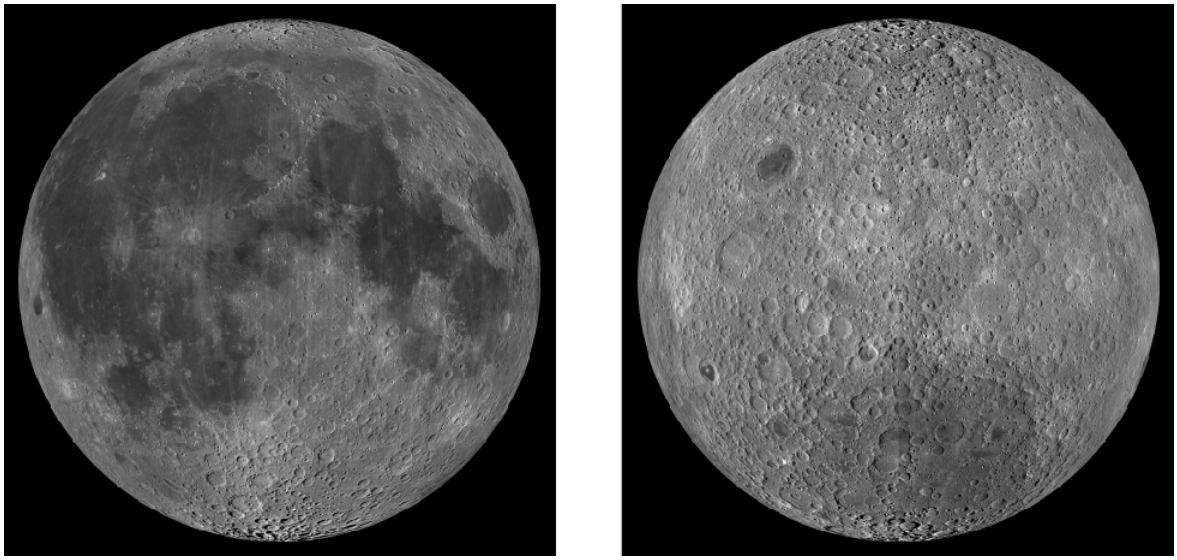


Figure 9.2 : Two Sides of the Moon. The left image shows part of the hemisphere that faces Earth; several dark maria are visible. The right image shows part of the hemisphere that faces away from Earth; it is dominated by highlands. The resolution of this image is several kilometers, similar to that of high-powered binoculars or a small telescope. (credit: modification of work by NASA/GSFC/Arizona State University)

Table 9.1: Properties of the Moon and Mercury

Property	Moon	Mercury
Mass (Earth = 1)	0.0123	0.055
Diameter (km)	3476	4878
Density (g/cm^3)	3.3	5.4
Surface gravity (Earth = 1)	0.17	0.38
Escape velocity (km/s)	2.4	4.3
Rotation period (days)	27.3	58.65
Surface area (Earth = 1)	0.27	0.38

Exploration of the Moon

Most of what we know about the Moon today derives from the US Apollo program, which sent nine piloted spacecraft to our satellite between 1968 and 1972, landing 12 astronauts on its surface (Figure 9.1). Before the era of spacecraft studies, astronomers

had mapped the side of the Moon that faces Earth with telescopic resolution of about 1 kilometer, but lunar geology hardly existed as a scientific subject. All that changed beginning in the early 1960s. Initially, Russia took the lead in lunar exploration with Luna 3, which returned the first photos of the lunar far side in 1959, and then with Luna 9, which landed on the surface in 1966 and transmitted pictures and other data to Earth. However, these efforts were overshadowed on July 20, 1969, when the first American astronaut set foot on the Moon.

Table 9.2 summarizes the nine Apollo flights: six that landed and three others that circled the Moon but did not land. The initial landings were on flat plains selected for safety reasons. But with increasing experience and confidence, NASA targeted the last three missions to more geologically interesting locales. The level of scientific exploration also increased with each mission, as the astronauts spent longer times on the Moon and carried more elaborate equipment. Finally, on the last Apollo landing, NASA included one scientist, geologist Jack Schmitt, among the astronauts (Figure 9.3).

Table 9.2: Apollo Flights to the Moon

Flight	Date	Landing Site	Main Accomplishment
Apollo 8	Dec. 1968	—	First humans to fly around the Moon
Apollo 10	May 1969	—	First spacecraft rendezvous in lunar orbit
Apollo 11	July 1969	Mare Tranquillitatis	First human landing on the Moon; 22 kilograms of samples returned
Apollo 12	Nov. 1969	Oceanus Procellarum	First Apollo Lunar Surface Experiment Package (ALSEP); visit to Surveyor 3 lander
Apollo 13	Apr. 1970	—	Landing aborted due to explosion in service module
Apollo 14	Jan. 1971	Mare Nubium	First “rickshaw” on the Moon
Apollo 15	July 1971	Mare Imbrium/Hadley	First “rover;” visit to Hadley Rille; astronauts traveled 24 kilometers
Apollo 16	Apr. 1972	Descartes	First landing in highlands; 95 kilograms of samples returned
Apollo 17	Dec. 1972	Taurus-Littrow highlands	Geologist among the crew; 111 kilograms of samples returned



Figure 9.3 : Scientist on the Moon. Geologist (and later US senator) Harrison “Jack” Schmitt in front of a large boulder in the Littrow Valley at the edge of the lunar highlands. Note how black the sky is on the airless Moon. No stars are visible because the surface is brightly lit by the Sun, and the exposure therefore is not long enough to reveal stars.

In addition to landing on the lunar surface and studying it at close range, the Apollo missions accomplished three objectives of major importance for lunar science. First, the astronauts collected nearly 400 kilograms of samples for detailed laboratory analysis on Earth (Figure 9.4). These samples have revealed as much about the Moon and its history as all other lunar studies combined. Second, each Apollo landing after the first one deployed an Apollo Lunar Surface Experiment Package (ALSEP), which continued to operate for years after the astronauts departed. Third, the orbiting Apollo command modules carried a wide range of instruments to photograph and analyze the lunar surface from above.



Figure 9.4 : Handling Moon Rocks. Lunar samples collected in the Apollo Project are analyzed and stored in NASA facilities at the Johnson Space Center in Houston, Texas. Here, a technician examines a rock sample using gloves in a sealed environment to avoid contaminating the sample. (credit: NASA JSC)

The last human left the Moon in December 1972, just a little more than three years after Neil Armstrong took his “giant leap for mankind.” The program of lunar exploration was cut off midstride due to political and economic pressures. It had cost just about $100 per American, spread over 10 years—the equivalent of one large pizza per person per year. Yet for many people, the Moon landings were one of the central events in twentieth-century history.

The giant Apollo rockets built to travel to the Moon were left to rust on the lawns of NASA centers in Florida, Texas, and Alabama, although recently, some have at least been moved indoors to museums (Figure 9.5). It is more than 50 years since astronauts landed on the Moon, and there are no firm plans for future flights. However, both the United States and China are developing the capability to land on the Moon, and there may be a new “space race” in the late 2020s. (In a bizarre piece of irony, a few people even question whether we went to the Moon at all, proposing instead that the Apollo program was a fake, filmed on a Hollywood sound stage. See the Link to Learning box below for some scientists’ replies to such claims.) However, scientific interest in the Moon is stronger than ever, and more than half a dozen scientific spacecraft—sent from NASA, ESA, Japan, India, and China—have orbited or landed on our nearest neighbor during the past two decades.x

Link to Learning

Read The Great Moon Hoax about the claim that NASA never succeeded in putting people on the Moon.

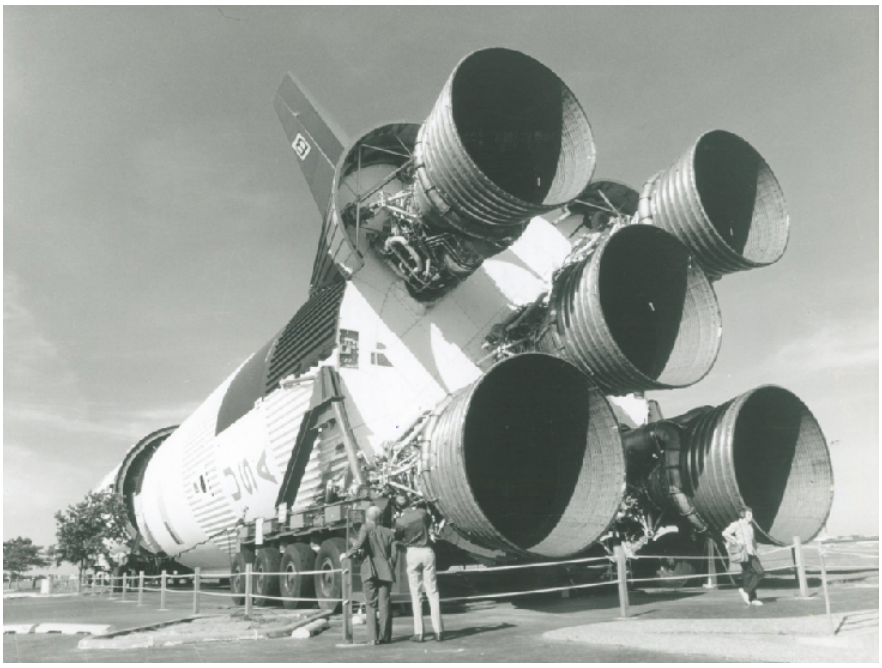


Figure 9.5 : Moon Rocket on Display. One of the unused Saturn 5 rockets built to go to the Moon is now a tourist attraction at NASA's Johnson Space Center in Houston, although it has been moved indoors since this photo was taken. (credit: modification of work by David Morrison)

Lunar exploration has become an international enterprise with many robotic spacecraft focusing on lunar science. The USSR sent a number in the 1960s, including robot sample returns, and recently China has been active, with three landers and a sample return mission. Of special interest is the search for accessible water ice near the lunar South Pole. Table 9.3 lists some of the most recent lunar missions.

Table 9.3: Some International Missions to the Moon

Launch Year	Spacecraft	Type of Mission	Agency
1994	Clementine	Orbiter	US (USAF/NASA)
1998	Lunar Prospector	Orbiter	US (NASA)
2003	SMART-1	Orbiter	Europe (ESA)
2007	SELENE 1	Orbiter	Japan (JAXA)
2007	Chang'e 1	Orbiter	China (CNSA)
2008	Chandrayaan-1	Orbiter	India (ISRO)
2009	LRO	Orbiter	US (NASA)
2009	LCROSS	Impactor	US (NASA)
2010	Chang'e 2	Orbiter	China (CNSA)
2011	GRAIL	Twin orbiters	US (NASA)

Launch Year	Spacecraft	Type of Mission	Agency
2013	LADEE	Orbiter	US (NASA)
2013	Chang'e 3	Lander/Rover	China (CNSA)
2019	Chang-e 4	Lander/Rover (far side)	China(CNSA)
2020	Chang-e 5	Lander/Sample Return	China(CNSA)

Composition and Structure of the Moon

The composition of the Moon is not the same as that of Earth. With an average density of only 3.3 g/cm^3, the Moon must be made almost entirely of silicate rock. Compared to Earth, it is depleted in iron and other metals. It is as if the Moon were composed of the same silicates as Earth's mantle and crust, with the metals and the volatiles selectively removed. These differences in composition between Earth and Moon provide important clues about the origin of the Moon, a topic we will cover in detail later in this chapter.

Studies of the Moon's interior carried out with seismometers taken to the Moon as part of the Apollo program confirm the absence of a large metal core. The twin GRAIL spacecraft launched into lunar orbit in 2011 provided even more precise tracking of the interior structure. We also know from the study of lunar samples that water and other volatiles have been depleted from the lunar crust. The tiny amounts of water detected in these samples were originally attributed to small leaks in the container seal that admitted water vapor from Earth's atmosphere. However, scientists have now concluded that some chemically bound water is present in the lunar rocks.

Most dramatically, water ice has been detected in permanently shadowed craters near the lunar poles. In 2009, NASA crashed a small spacecraft called the Lunar Crater Observation and Sensing Satellite (LCROSS) into the crater Cabeus near the Moon's south pole. The impact at 9,000 kilometers per hour released energy equivalent to 2 tons of dynamite, blasting a plume of water vapor and other chemicals high above the surface. This plume was visible to telescopes in orbit around the Moon, and the LCROSS spacecraft itself made measurements as it flew through the plume. A NASA spacecraft called the Lunar Reconnaissance Orbiter (LRO) also measured the very low temperatures inside several lunar craters, and its sensitive cameras were even able to image crater interiors by starlight.

The total quantity of water ice in the Moon's polar craters is estimated to be hundreds of billions of tons. As liquid, this would only be enough water to fill a lake 100 miles across, but compared with the rest of the dry lunar crust, so much water is remarkable. Presumably, this polar water was carried to the Moon by comets and asteroids that hit its surface. Some small fraction of the water froze in a few extremely cold regions (cold traps) where the Sun never shines, such as the bottom of deep craters at the Moon's poles. One reason this discovery could be important is that it raises the possibility of future human habitation near the lunar poles, or even of a lunar base as a way-station on routes to Mars and the rest of the solar system. If the ice could be mined, it would yield both water and oxygen for human support, and it could be broken down into hydrogen and oxygen, a potent rocket fuel.

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8.3: The Lunar Surface

Learning Objectives

By the end of this section, you will be able to:

- Differentiate between the major surface features of the Moon
- Describe the history of the lunar surface
- Describe the properties of the lunar "soil"

General Appearance

If you look at the Moon through a telescope, you can see that it is covered by impact craters of all sizes. The most conspicuous of the Moon's surface features—those that can be seen with the unaided eye and that make up the feature often called "the man in the Moon"—are vast splotches of darker lava flows.

Centuries ago, early lunar observers thought that the Moon had continents and oceans and that it was a possible abode of life. They called the dark areas "seas" (*maria* in Latin, or *mare* in the singular, pronounced "mah ray"). Their names, Mare Nubium (Sea of Clouds), Mare Tranquillitatis (Sea of Tranquility), and so on, are still in use today. In contrast, the "land" areas between the seas are not named. Thousands of individual craters have been named, however, mostly for great scientists and philosophers (Figure 9.6). Among the most prominent craters are those named for Plato, Copernicus, Tycho, and Kepler. Galileo only has a small crater, however, reflecting his low standing among the Vatican scientists who made some of the first lunar maps.

We know today that the resemblance of lunar features to terrestrial ones is superficial. Even when they look somewhat similar, the origins of lunar features such as craters and mountains are very different from their terrestrial counterparts. The Moon's relative lack of internal activity, together with the absence of air and water, make most of its geological history unlike anything we know on Earth.

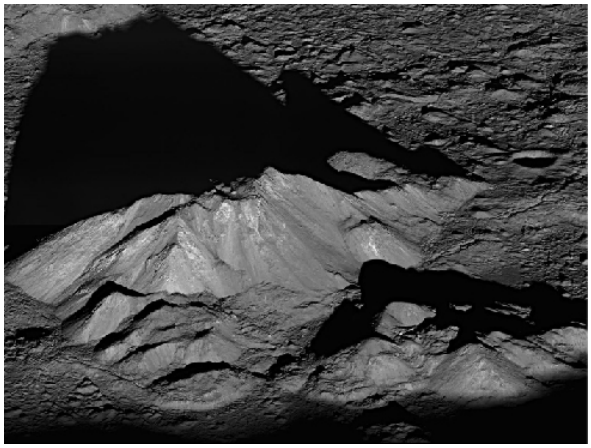


Figure 9.6 : Sunrise on the Central Mountain Peaks of Tycho Crater, as Imaged by the NASA Lunar Reconnaissance Orbiter. Tycho, about 82 kilometers in diameter, is one of the youngest of the very large lunar craters. The central mountain rises 2 kilometers above the crater floor. (credit: modification of work by NASA/Goddard/Arizona State University)

Lunar History

To trace the detailed history of the Moon or of any planet, we must be able to estimate the ages of individual rocks. Once lunar samples were brought back by the Apollo astronauts, the radioactive dating techniques that had been developed for Earth were applied to them. The solidification ages of the samples ranged from about 3.3 to 4.4 billion years old, substantially older than most of the rocks on Earth. For comparison, as we saw in the chapter on Earth, Moon, and Sky, both Earth and the Moon were formed between 4.5 and 4.6 billion years ago.

Most of the crust of the Moon (83%) consists of silicate rocks called *anorthosites*; these regions are known as the lunar highlands. They are made of relatively low-density rock that solidified on the cooling Moon like slag floating on the top of a smelter. Because they formed so early in lunar history (between 4.1 and 4.4 billion years ago), the highlands are also extremely heavily cratered, bearing the scars of all those billions of years of impacts by interplanetary debris (Figure 9.7).



Figure 9.7 : Lunar Highlands. The old, heavily cratered lunar highlands make up 83% of the Moon's surface. (credit: Apollo 11 Crew, NASA)

Unlike the mountains on Earth, the Moon's highlands do not have any sharp folds in their ranges. The highlands have low, rounded profiles that resemble the oldest, most eroded mountains on Earth (Figure 9.8). Because there is no atmosphere or water on the Moon, there has been no wind, water, or ice to carve them into cliffs and sharp peaks, the way we have seen them shaped on Earth. Their smooth features are attributed to gradual erosion, mostly due to impact cratering.

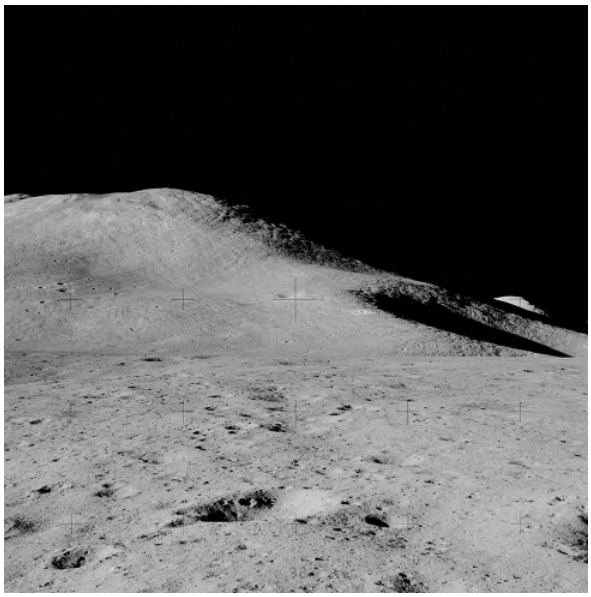


Figure 9.8 : Lunar Mountain. This photo of Mt. Hadley on the edge of Mare Imbrium was taken by Dave Scott, one of the Apollo 15 astronauts. Note the smooth contours of the lunar mountains, which have not been sculpted by water or ice. (credit: NASA/Apollo Lunar Surface Journal)

The maria are much less cratered than the highlands, and cover just 17% of the lunar surface, mostly on the side of the Moon that faces Earth (Figure 9.9).

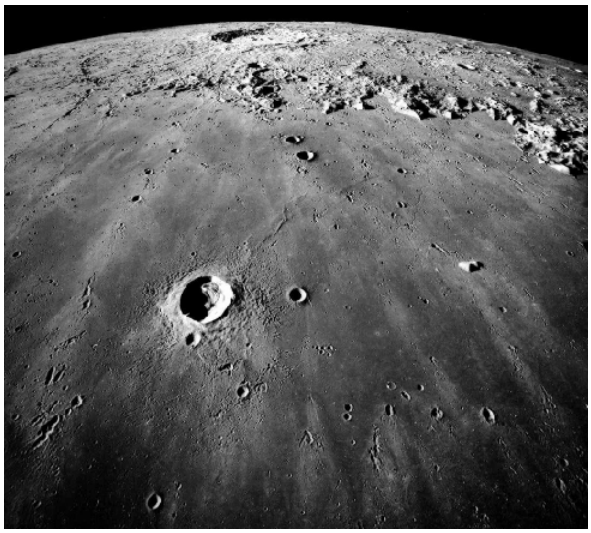


Figure 9.9 : Lunar Maria. About 17% of the Moon's surface consists of the maria—flat plains of basaltic lava. This view of Mare Imbrium also shows numerous secondary craters and evidence of material ejected from the large crater Copernicus on the upper horizon. Copernicus is an impact crater almost 100 kilometers in diameter that was formed long after the lava in Imbrium had already been deposited. (credit: NASA, Apollo 17)

Today, we know that the maria consist mostly of dark-colored basalt (volcanic lava) laid down in volcanic eruptions billions of years ago. Eventually, these lava flows partly filled the huge depressions called *impact basins*, which had been produced by collisions of large chunks of material with the Moon relatively early in its history. The basalt on the Moon (Figure 9.10) is very similar in composition to the crust under the oceans of Earth or to the lavas erupted by many terrestrial volcanoes. The youngest of the lunar impact basins is Mare Orientale, shown in Figure 9.11.



Figure 9.10 : Rock from a Lunar Mare. In this sample of basalt from the mare surface, you can see the holes left by gas bubbles, which are characteristic of rock formed from lava. All lunar rocks are chemically distinct from terrestrial rocks, a fact that has allowed scientists to identify a few lunar samples among the thousands of meteorites that reach Earth. (credit: modification of work by NASA)

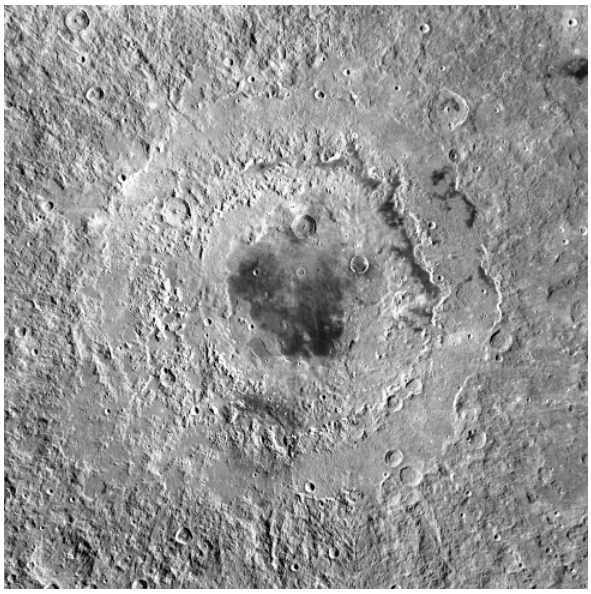


Figure 9.11 : Mare Orientale. The youngest of the large lunar impact basins is Orientale, formed 3.8 billion years ago. Its outer ring is about 1000 kilometers in diameter, roughly the distance between New York City and Detroit, Michigan. Unlike most of the other basins, Orientale has not been completely filled in with lava flows, so it retains its striking "bull's-eye" appearance. It is located on the edge of the Moon as seen from Earth. (credit: NASA)

Volcanic activity may have begun very early in the Moon's history, although most evidence of the first half billion years is lost. What we do know is that the major mare volcanism, which involved the release of lava from hundreds of kilometers below the surface, ended about 3.3 billion years ago. After that, the Moon's interior cooled, and volcanic activity was limited to a very few small areas. The primary forces altering the surface come from the outside, not the interior.

On the Lunar Surface

"The surface is fine and powdery. I can pick it up loosely with my toe. But I can see the footprints of my boots and the treads in the fine sandy particles." —Neil Armstrong, Apollo 11 astronaut, immediately after stepping onto the Moon for the first time.

The surface of the Moon is buried under a fine-grained soil of tiny, shattered rock fragments. The dark basaltic dust of the lunar maria was kicked up by every astronaut footstep, and thus eventually worked its way into all of the astronauts' equipment. The upper layers of the surface are porous, consisting of loosely packed dust into which their boots sank several centimeters (Figure 9.12). This lunar dust, like so much else on the Moon, is the product of impacts. Each cratering event, large or small, breaks up the rock of the lunar surface and scatters the fragments. Ultimately, billions of years of impacts have reduced much of the surface layer to particles about the size of dust or sand.



Figure 9.12 : Footprint on Moon Dust. Apollo photo of an astronaut's boot print in the lunar soil. (credit: NASA)

In the absence of any air, the lunar surface experiences much greater temperature extremes than the surface of Earth, even though Earth is virtually the same distance from the Sun. Near local noon, when the Sun is highest in the sky, the temperature of the dark lunar soil rises above the boiling point of water. During the long lunar night (which, like the lunar day, lasts two Earth weeks[1]), the temperature drops to about 100 K (–173 °C). The extreme cooling is a result not only of the absence of air but also of the porous nature of the Moon's dusty soil, which cools more rapidly than solid rock would.

Link to Learning

Learn how the moon's craters and maria were formed by watching a video produced by NASA's Lunar Reconnaissance Orbiter (LRO) team about the evolution of the Moon, tracing it from its origin about 4.5 billion years ago to the Moon we see today. See a simulation of how the Moon's craters and maria were formed through periods of impact, volcanic activity, and heavy bombardment.

Footnotes

- 1You can see the cycle of day and night on the side of the Moon facing us in the form of the Moon's phases. It takes about 14 days for the side of the Moon facing us to go from full moon (all lit up) to new moon (all dark). There is more on this in Chapter 4: Earth, Moon, and Sky.

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8.4: Impact Craters

Learning Objectives

By the end of this section, you will be able to:

- Compare and contrast ideas about how lunar craters form
- Explain the process of impact crater formation
- Discuss the use of crater counts to determine relative ages of lunar landforms

Volcanic Versus Impact Origin of Craters

The Moon provides an important benchmark for understanding the history of our planetary system. Most solid worlds show the effects of impacts, often extending back to the era when a great deal of debris from our system's formation process was still present. On Earth, this long history has been erased by our active geology. On the Moon, in contrast, most of the impact history is preserved. If we can understand what has happened on the Moon, we may be able to apply this knowledge to other worlds. The Moon is especially interesting because it is not just any moon, but *our* Moon—a nearby world that has shared the history of Earth for more than 4 billion years and preserved a record that, for Earth, has been destroyed by our active geology.

Until the middle of the twentieth century, scientists did not generally recognize that lunar craters were the result of impacts. Since impact craters are extremely rare on Earth, geologists did not expect them to be the major feature of lunar geology. They reasoned (perhaps unconsciously) that since the craters we have on Earth are volcanic, the lunar craters must have a similar origin.

One of the first geologists to propose that lunar craters were the result of impacts was Grove K. Gilbert, a scientist with the US Geological Survey in the 1890s. He pointed out that the large lunar craters—mountain-rimmed, circular features with floors generally below the level of the surrounding plains—are larger and have different shapes from known volcanic craters on Earth. Terrestrial volcanic craters are smaller and deeper and almost always occur at the tops of volcanic mountains (Figure 9.13). The only alternative to explain the Moon's craters was an impact origin. His careful reasoning, although not accepted at the time, laid the foundations for the modern science of lunar geology.

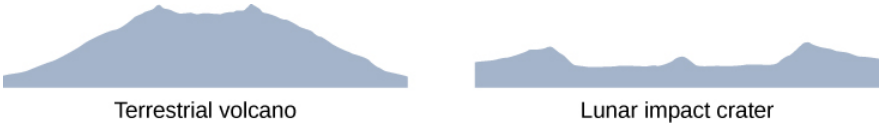


Figure 9.13 : Volcanic and Impact Craters. Profiles of a typical terrestrial volcanic crater and a typical lunar impact crater are quite different.

Gilbert concluded that the lunar craters were produced by impacts, but he didn't understand why all of them were circular and not oval. The reason lies in the escape velocity, the minimum speed that a body must reach to permanently break away from the gravity of another body; it is also the minimum speed that a projectile approaching Earth or the Moon will hit with. Attracted by the gravity of the larger body, the incoming chunk strikes with at least escape velocity, which is 11 kilometers per second for Earth and 2.4 kilometers per second (5400 miles per hour) for the Moon. To this escape velocity is added whatever speed the projectile already had with respect to Earth or Moon, typically 10 kilometers per second or more.

At these speeds, the energy of impact produces a violent *explosion* that excavates a large volume of material in a symmetrical way. Photographs of bomb and shell craters on Earth confirm that explosion craters are always essentially circular. Only following World War I did scientists recognize the similarity between impact craters and explosion craters, but, sadly, Gilbert did not live to see his impact hypothesis widely accepted.

The Cratering Process

Let's consider how an impact at these high speeds produces a crater. When such a fast projectile strikes a planet, it penetrates two or three times its own diameter before stopping. During these few seconds, its energy of motion is transferred into a shock wave (which spreads through the target body) and into heat (which vaporizes most of the projectile and some of the surrounding target). The shock wave fractures the rock of the target, while the expanding silicate vapor generates an explosion similar to that of a nuclear bomb detonated at ground level (Figure 9.14). The size of the excavated crater depends primarily on the speed of impact, but generally it is 10 to 15 times the diameter of the projectile.

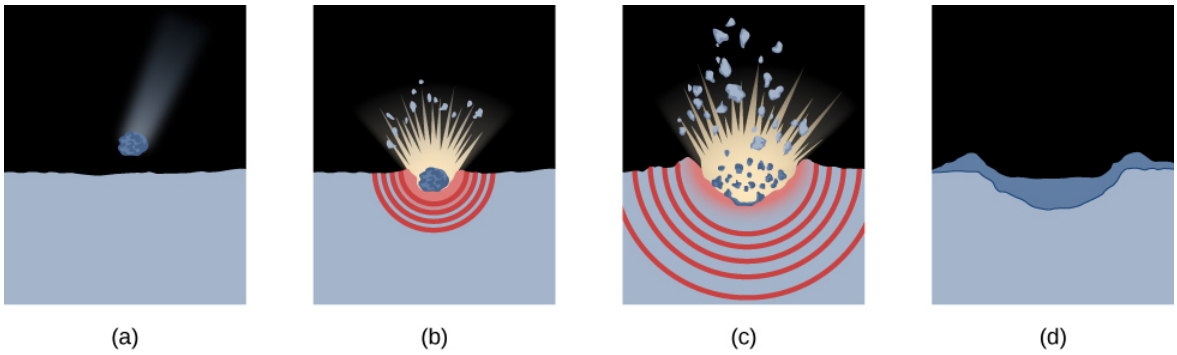


Figure 9.14 : Stages in the Formation of an Impact Crater. (a) The impact occurs. (b) The projectile vaporizes and a shock wave spreads through the lunar rock. (c) Ejecta are thrown out of the crater. (d) Most of the ejected material falls back to fill the crater, but some of it is found outside the crater in the form of an ejecta blanket.

An impact explosion of the sort described above leads to a characteristic kind of crater, as shown in Figure 9.15. The central cavity is initially bowl-shaped (the word “crater” comes from the Greek word for “bowl”), but the rebound of the crust partially fills it in, producing a flat floor and sometimes creating a central peak. Around the rim, landslides create a series of terraces.

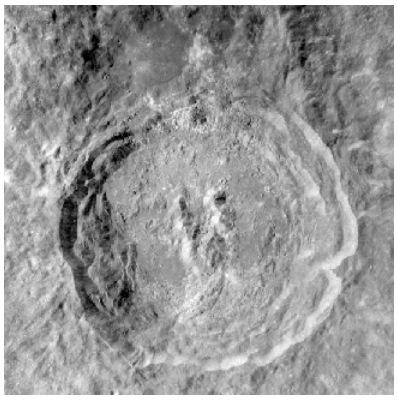


Figure 9.15 : Typical Impact Crater. King Crater on the far side of the Moon, a fairly recent lunar crater 75 kilometers in diameter, shows most of the features associated with large impact structures. (credit: NASA/JSC/Arizona State University)

The rim of the crater is turned up by the force of the explosion, so it rises above both the floor and the adjacent terrain. Surrounding the rim is an *ejecta blanket* consisting of material thrown out by the explosion. This debris falls back to create a rough, hilly region, typically about as wide as the crater diameter. Additional, higher-speed ejecta fall at greater distances from the crater, often digging small *secondary craters* where they strike the surface (Figure 9.9).

Some of these streams of ejecta can extend for hundreds or even thousands of kilometers from the crater, creating the bright *crater rays* that are prominent in lunar photos taken near full phase. The brightest lunar crater rays are associated with large young craters such as Kepler and Tycho.

Seeing for Yourself: Observing the Moon

The Moon is one of the most beautiful sights in the sky, and it is the only object close enough to reveal its *topography* (surface features such as mountains and valleys) without a visit from a spacecraft. A fairly small amateur telescope easily shows craters and mountains on the Moon as small as a few kilometers across.

Even as seen through a good pair of binoculars, we can observe that the appearance of the Moon’s surface changes dramatically with its phase. At full phase, it shows almost no topographic detail, and you must look closely to see more than a few craters. This is because sunlight illuminates the surface straight on, and in this flat lighting, no shadows are cast. Much more revealing is the view near first or third quarter, when sunlight streams in from the side, causing topographic features to cast sharp shadows. It is almost always more rewarding to study a planetary surface under such oblique lighting, when the maximum information about surface relief can be obtained.

The flat lighting at full phase does, however, accentuate brightness contrasts on the Moon, such as those between the maria and highlands. Notice in Figure 9.16 that several of the large mare craters seem to be surrounded by white material and that the light streaks or rays that can stretch for hundreds of kilometers across the surface are clearly visible. These lighter features are ejecta, splashed out from the crater-forming impact.



Figure 9.16 : Appearance of the Moon at Different Phases. (a) Illumination from the side brings craters and other topographic features into sharp relief, as seen on the far left side. (b) At full phase, there are no shadows, and it is more difficult to see such features. However, the flat lighting at full phase brings out some surface features, such as the bright rays of ejecta that stretch out from a few large young craters. (credit: modification of work by Luc Viatour)

By the way, there is no danger in looking at the Moon with binoculars or telescopes. The reflected sunlight is never bright enough to harm your eyes. In fact, the sunlit surface of the Moon has about the same brightness as a sunlit landscape of dark rock on Earth. Although the Moon looks bright in the night sky, its surface is, on average, much less reflective than Earth's, with its atmosphere and white clouds. This difference is nicely illustrated by the photo of the Moon passing in front of Earth taken from the Deep Space Climate Observatory spacecraft (Figure 9.17). Since the spacecraft took the image from a position inside the orbit of Earth, we see both objects fully illuminated (full Moon and full Earth). By the way, you cannot see much detail on the Moon because the exposure has been set to give a bright image of Earth, not the Moon.



Figure 9.17 : The Moon Crossing the Face of Earth. In this 2015 image from the Deep Space Climate Observatory spacecraft, both objects are fully illuminated, but the Moon looks darker because it has a much lower average reflectivity than Earth. (credit: modification of work by NASA, DSCOVR EPIC team)

One interesting thing about the Moon that you can see without binoculars or telescopes is popularly called "the new Moon in the old Moon's arms." Look at the Moon when it is a thin crescent, and you can often make out the faint circle of the entire lunar disk, even though the sunlight shines on only the crescent. The rest of the disk is illuminated not by sunlight but by earthlight—sunlight reflected from Earth. The light of the full Earth on the Moon is about 50 times brighter than that of the full Moon shining on Earth.

Using Crater Counts

If a world has had little erosion or internal activity, like the Moon during the past 3 billion years, it is possible to use the number of impact craters on its surface to estimate the age of that surface. By “age” here we mean the time since a major disturbance occurred on that surface (such as the volcanic eruptions that produced the lunar maria).

We cannot directly measure the rate at which craters are being formed on Earth and the Moon, since the average interval between large crater-forming impacts is longer than the entire span of human history. Our best-known example of such a large crater, Meteor Crater in Arizona (Figure 9.18), is about 50,000 years old. However, the cratering rate can be estimated from the number of craters on the lunar maria or calculated from the number of potential “projectiles” (asteroids and comets) present in the solar system today. Both lines of reasoning lead to about the same estimations.



Figure 9.18 : Meteor Crater. This aerial photo of Meteor Crater in Arizona shows the simple form of a meteorite impact crater. The crater’s rim diameter is about 1.2 kilometers. (credit: Shane Torgerson)

For the Moon, these calculations indicate that a crater 1 kilometer in diameter should be produced about every 200,000 years, a 10-kilometer crater every few million years, and one or two 100-kilometer craters every billion years. If the cratering rate has stayed the same, we can figure out how long it must have taken to make all the craters we see in the lunar maria. Our calculations show that it would have taken several billion years. This result is similar to the age determined for the maria from radioactive dating of returned samples—3.3 to 3.8 billion years old.

The fact that these two calculations agree suggests that astronomers’ original assumption was right: comets and asteroids in approximately their current numbers have been impacting planetary surfaces for billions of years. Calculations carried out for other planets (and their moons) indicate that they also have been subject to about the same number of interplanetary impacts during this time.

We have good reason to believe, however, that earlier than 3.8 billion years ago, the impact rates must have been a great deal higher. This becomes immediately evident when comparing the numbers of craters on the lunar highlands with those on the maria. Typically, there are 10 times more craters on the highlands than on a similar area of maria. Yet the radioactive dating of highland samples showed that they are only a little older than the maria, typically 4.2 billion years rather than 3.8 billion years. If the rate of impacts had been constant throughout the Moon’s history, the highlands would have had to be at least 10 times older. They would thus have had to form 38 billion years ago—long before the universe itself began.

In science, when an assumption leads to an implausible conclusion, we must go back and re-examine that assumption—in this case, the constant impact rate. The contradiction is resolved if the impact rate varied over time, with a much heavier bombardment earlier than 3.8 billion years ago (Figure 9.19). This “heavy bombardment” produced most of the craters we see today in the highlands.

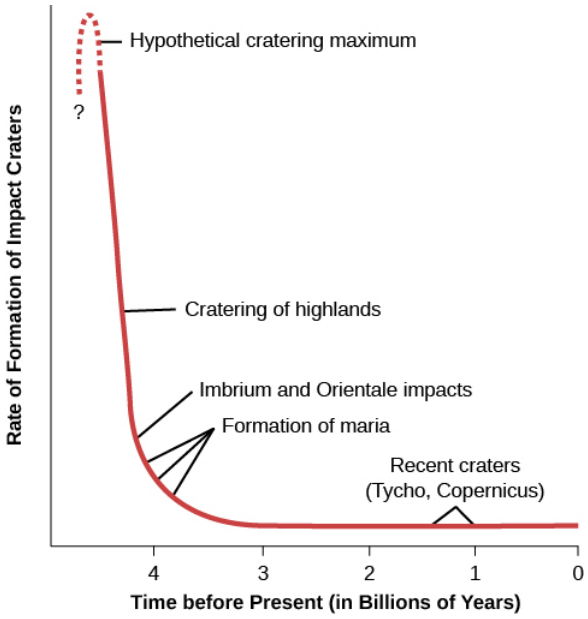


Figure 9.19 : Cratering Rates over Time. The number of craters being made on the Moon's surface has varied with time over the past 4.3 billion years.

This idea we have been exploring—that large impacts (especially during the early history of the solar system) played a major role in shaping the worlds we see—is not unique to our study of the Moon. As you read through the other chapters about the planets, you will see further indications that a number of the present-day characteristics of our system may be due to its violent past.

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8.5: The Origin of the Moon

Learning Objectives

By the end of this section, you will be able to:

- Describe the top three early hypotheses of the formation of the Moon
- Summarize the current "giant impact" concept of how the Moon formed

Ideas for the Origin of the Moon

It is characteristic of modern science to ask how things originated. Understanding the origin of the Moon has proven to be challenging for planetary scientists, however. Part of the difficulty is simply that we know so much about the Moon (quite the opposite of our usual problem in astronomy). As we will see, one key problem is that the Moon is both tantalizingly similar to Earth and frustratingly different.

Most of the earlier hypotheses for the Moon's origin followed one of three general ideas:

1. The fission theory—the Moon was once part of Earth, but somehow separated from it early in their history.
2. The sister theory—the Moon formed together with (but independent of) Earth, as we believe many moons of the outer planets formed.
3. The capture theory—the Moon formed elsewhere in the solar system and was captured by Earth.

Unfortunately, there seem to be fundamental problems with each of these ideas. Perhaps the easiest hypothesis to reject is the capture theory. Its primary drawback is that no one knows of any way that early Earth could have captured such a large moon from elsewhere. One body approaching another cannot go into orbit around it without a substantial loss of energy; this is the reason that spacecraft destined to orbit other planets are equipped with retro-rockets. Furthermore, if such a capture did take place, the captured object would go into a very eccentric orbit rather than the nearly circular orbit our Moon occupies today. Finally, there are too many compositional similarities between Earth and the Moon, particularly an identical fraction of the major isotopes[2] of oxygen, to justify seeking a completely independent origin.

The fission hypothesis, which states that the Moon separated from Earth, was suggested in the late nineteenth century. Modern calculations have shown that this sort of spontaneous fission or splitting is impossible. Furthermore, it is difficult to understand how a Moon made out of terrestrial material in this way could have developed the many distinctive chemical differences now known to characterize our neighbor.

Scientists were therefore left with the sister hypothesis—that the Moon formed alongside Earth—or with some modification of the fission hypothesis that can find a more acceptable way for the lunar material to have separated from Earth. But the more we learned about our Moon, the less these old ideas seem to fit the bill.

The Giant Impact Hypothesis

In an effort to resolve these apparent contradictions, scientists developed a fourth hypothesis for the origin of the Moon, one that involves a giant impact early in Earth's history. There is increasing evidence that large chunks of material—objects of essentially planetary mass—were orbiting in the inner solar system at the time that the terrestrial planets formed. The giant impact hypothesis envisions Earth being struck obliquely by an object approximately one-tenth Earth's mass—a "bullet" about the size of Mars. This is very nearly the largest impact Earth could experience without being shattered.

Such an impact would disrupt much of Earth and eject a vast amount of material into space, releasing almost enough energy to break the planet apart. Computer simulations indicate that material totaling several percent of Earth's mass could be ejected in such an impact. Most of this material would be from the stony mantles of Earth and the impacting body, not from their metal cores. This ejected rock vapor then cooled and formed a ring of material orbiting Earth. It was this ring that ultimately condensed into the Moon.

While we do not have any current way of showing that the giant impact hypothesis is the correct model of the Moon's origin, it does offer potential solutions to most of the major problems raised by the chemistry of the Moon. First, since the Moon's raw material is derived from the mantles of Earth and the projectile, the absence of metals is easily understood. Second, most of the volatile elements would have been lost during the high-temperature phase following the impact, explaining the lack of these

materials on the Moon. Yet, by making the Moon primarily of terrestrial mantle material, it is also possible to understand similarities such as identical abundances of various oxygen isotopes.

Footnotes

- 2Remember from the Radiation and Spectra chapter that the term isotope means a different “version” of an element. Specifically, different isotopes of the same element have equal numbers of protons but different numbers of neutrons (as in carbon-12 versus carbon-14.)

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8.6: Key Terms

highlands

the lighter, heavily cratered regions of the Moon, which are generally several kilometers higher than the maria

mare

(plural: maria) Latin for “sea;” the name applied to the dark, relatively smooth features that cover 17% of the Moon’s surface

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8.7: Summary

9.1 General Properties of the Moon

Most of what we know about the Moon derives from the Apollo program, including 400 kilograms of lunar samples still being intensively studied. The Moon has one-eightieth the mass of Earth and is severely depleted in both metals and volatile materials. It is made almost entirely of silicates like those in Earth's mantle and crust. However, more recent spacecraft have found evidence of a small amount of water near the lunar poles, most likely deposited by comet and asteroid impacts.

9.2 The Lunar Surface

The Moon, like Earth, was formed about 4.5 billion year ago. The Moon's heavily cratered highlands are made of rocks more than 4 billion years old. The darker volcanic plains of the maria were erupted primarily between 3.3 and 3.8 billion years ago. Generally, the surface is dominated by impacts, including continuing small impacts that produce its fine-grained soil.

9.3 Impact Craters

A century ago, Grove Gilbert suggested that the lunar craters were caused by impacts, but the cratering process was not well understood until more recently. High-speed impacts produce explosions and excavate craters 10 to 15 times the size of the impactor with raised rims, ejecta blankets, and often central peaks. Cratering rates have been roughly constant for the past 3 billion years but earlier were much greater. Crater counts can be used to derive approximate ages for geological features on the Moon and other worlds with solid surfaces.

9.4 The Origin of the Moon

The three standard hypotheses for the origin of the Moon were the fission hypothesis, the sister hypothesis, and the capture hypothesis. All have problems, and they have been supplanted by the giant impact hypothesis, which ascribes the origin of the Moon to the impact of a Mars-sized projectile with Earth 4.5 billion years ago. The debris from the impact made a ring around Earth which condensed and formed the Moon.

9.5 Mercury

Mercury is the nearest planet to the Sun and the fastest moving. Mercury is similar to the Moon in having a heavily cratered surface and no atmosphere, but it differs in having a very large metal core. Early in its evolution, it apparently lost part of its silicate mantle, probably due to one or more giant impacts. Long scarps on its surface testify to a global compression of Mercury's crust during the past 4 billion years.

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The Moon

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Lunar & Planetary Institute: www.lpi.usra.edu/lunar/missions/. Lunar Science and Exploration web pages.

Lunar Reconnaissance Orbiter Mission Page: http://lro.gsfc.nasa.gov/.

NASA's Guide to Moon Missions and Information: http://nssdc.gsfc.nasa.gov/planetary/planets/moonpage.html.

Origin of the Moon: http://www.psi.edu/projects/moon/moon.html. By William Hartmann, who, with a colleague, first suggested the giant impact hypothesis for how the Moon formed, in 1975.

Sky & Telescope magazine's observing guides and articles about the Moon: www.skyandtelescope.com/observing/celestial-objects-to-watch/moon/.

To the Moon: http://www.pbs.org/wgbh/nova/tothemoon/. PBS program on the Apollo landings.

Mercury

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MESSENGER Mission Website: http://messenger.jhuapl.edu/.

NASA Planetary Data Center Mercury Page: http://nssdc.gsfc.nasa.gov/planetary/planets/mercurypage.html.

Views of the Solar System Mercury Page: http://solarviews.com/eng/mercury.htm.

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8.9: Collaborative Group Activities

A. We mentioned that no nation on Earth now has the capability to send a human being to the Moon, even though the United States once sent 12 astronauts to land there. What does your group think about this? Should we continue the exploration of space with human beings? Should we put habitats on the Moon? Should we go to Mars? Does humanity have a “destiny in space?” Whatever your answer to these questions, make a list of the arguments and facts that support your position.

B. When they hear about the giant impact hypothesis for the origin of the Moon, many students are intrigued and wonder why we can’t cite more evidence for it. In your group, make a list of reasons we cannot find any traces on Earth of the great impact that formed the Moon?

C. We discussed that the ice (mixed into the soil) that is found on the Moon was most likely delivered by comets. Have your group make a list of all the reasons the Moon would not have any ice of its own left over from its early days.

D. Can your group make a list of all the things that would be different if Earth had no Moon? Don’t restrict your answer to astronomy and geology. Think about our calendars and moonlit romantic strolls, for example. (You may want to review Earth, Moon, and Sky.)

E. If, one day, humanity decides to establish a colony on the Moon, where should we put it? Make a list of the advantages and disadvantages of locating such a human habitat on the near side, the far side, or at the poles. What site would be best for doing visible-light and radio astronomy from observatories on the Moon?

F. A member of the class (but luckily, not a member of your group) suggests that he has always dreamed of building a vacation home on the planet Mercury. Can your group make a list of all reasons such a house would be hard to build and keep in good repair?

G. As you’ve read in this chapter, craters on the Moon are (mostly) named after scientists. (See the official list at: planetarynames.wr.usgs.gov/Se...ter,%20craters). The craters on Mercury, on the other hand, are named for writers, artists, composers, and others in the humanities. See the official list at: planetarynames.wr.usgs.gov/Se...ter,%20craters). Living persons are not eligible. Can each person in your group think of a scientist or someone in the arts whom they especially respect? Now check to see if they are listed. Are there scientists or people in the arts who should have their names on the Moon or Mercury and do not?

H. Imagine that a distant relative, hearing you are taking an astronomy course, calls you up and tells you that NASA faked the Moon landings. His most significant argument is that all the photos of the Moon show black skies, but none of them have any stars showing. This proves that the photos were taken against a black backdrop in a studio and not on the Moon. Based on your reading in this chapter, what arguments can your group come up with to rebut this idea?

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8.10.1: Review Questions

Review Questions

1.

What is the composition of the Moon, and how does it compare to the composition of Earth? Of Mercury?

2.

Why does the Moon not have an atmosphere?

3.

What are the principal features of the Moon observable with the unaided eye?

4.

Frozen water exists on the lunar surface primarily in which location? Why?

5.

Outline the main events in the Moon’s geological history.

6.

What are the maria composed of? Is this material found elsewhere in the solar system?

7.

The mountains on the Moon were formed by what process?

8.

With no wind or water erosion of rocks, what is the mechanism for the creation of the lunar “soil?”

9.

What differences did Grove K. Gilbert note between volcanic craters on Earth and lunar craters?

10.

Explain how high-speed impacts form circular craters. How can this explanation account for the various characteristic features of impact craters?

11.

Explain the evidence for a period of heavy bombardment on the Moon about 4 billion years ago.

12.

How did our exploration of the Moon differ from that of Mercury (and the other planets)?

13.

Summarize the four main hypotheses for the origin of the Moon.

14.

What are the difficulties with the capture hypothesis of the Moon’s origin?

15.

What is the main consequence of Mercury’s orbit being so highly eccentric?

16.

Describe the basic internal structure of Mercury.

17.

How was the rotation rate of Mercury determined?

18.

What is the relationship between Mercury’s rotational period and orbital period?

19.

The features of Mercury are named in honor of famous people in which fields of endeavor?

20.

What do our current ideas about the origins of the Moon and Mercury have in common? How do they differ?

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8.10.2: Thought Questions

Thought Questions

21.

One of the primary scientific objectives of the Apollo program was the return of lunar material. Why was this so important? What can be learned from samples? Are they still of value now?

22.

Apollo astronaut David Scott dropped a hammer and a feather together on the Moon, and both reached the ground at the same time. What are the two distinct advantages that this experiment on the Moon had over the same kind of experiment as performed by Galileo on Earth?

23.

Galileo thought the lunar maria might be seas of water. If you had no better telescope than the one he had, could you demonstrate that they are not composed of water?

24.

Why did it take so long for geologists to recognize that the lunar craters had an impact origin rather than a volcanic one?

25.

How might a crater made by the impact of a comet with the Moon differ from a crater made by the impact of an asteroid?

26.

Why are the lunar mountains smoothly rounded rather than having sharp, pointed peaks (as they were almost always depicted in science-fiction illustrations and films before the first lunar landings)?

27.

The lunar highlands have about ten times more craters in a given area than do the maria. Does this mean that the highlands are 10 times older? Explain your reasoning.

28.

At the end of the section on the lunar surface, your authors say that lunar night and day each last about two Earth weeks. After looking over the information in Earth, Moon, and Sky and this chapter about the motions of the Moon, can you explain why? (It helps to draw a diagram for yourself.)

29.

Give several reasons Mercury would be a particularly unpleasant place to build an astronomical observatory.

30.

If, in the remote future, we establish a base on Mercury, keeping track of time will be a challenge. Discuss how to define a year on Mercury, and the two ways to define a day. Can you come up with ways that humans raised on Earth might deal with time cycles on Mercury?

31.

The Moon has too little iron, Mercury too much. How can both of these anomalies be the result of giant impacts? Explain how the same process can yield such apparently contradictory results.

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8.10.3: Figuring for Yourself

Figuring for Yourself

32.

In the future, astronomers discover a solid moon around a planet orbiting one of the nearest stars. This moon has a diameter of 1948 km and a mass of 1.6×10^{22} kg. What is its density?

33.

The Moon was once closer to Earth than it is now. When it was at half its present distance, how long was its period of revolution? (See Orbits and Gravity for the formula to use.)

34.

Astronomers believe that the deposit of lava in the giant mare basins did not happen in one flow but in many different eruptions spanning some time. Indeed, in any one mare, we find a variety of rock ages, typically spanning about 100 million years. The individual lava flows as seen in Hadley Rille by the Apollo 15 astronauts were about 4 m thick. Estimate the average time interval between the beginnings of successive lava flows if the total depth of the lava in the mare is 2 km.

35.

The Moon requires about 1 month (0.08 year) to orbit Earth. Its distance from us is about 400,000 km (0.0027 AU). Use Kepler’s third law, as modified by Newton, to calculate the mass of Earth relative to the Sun.

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